Higgs Searches at CDF

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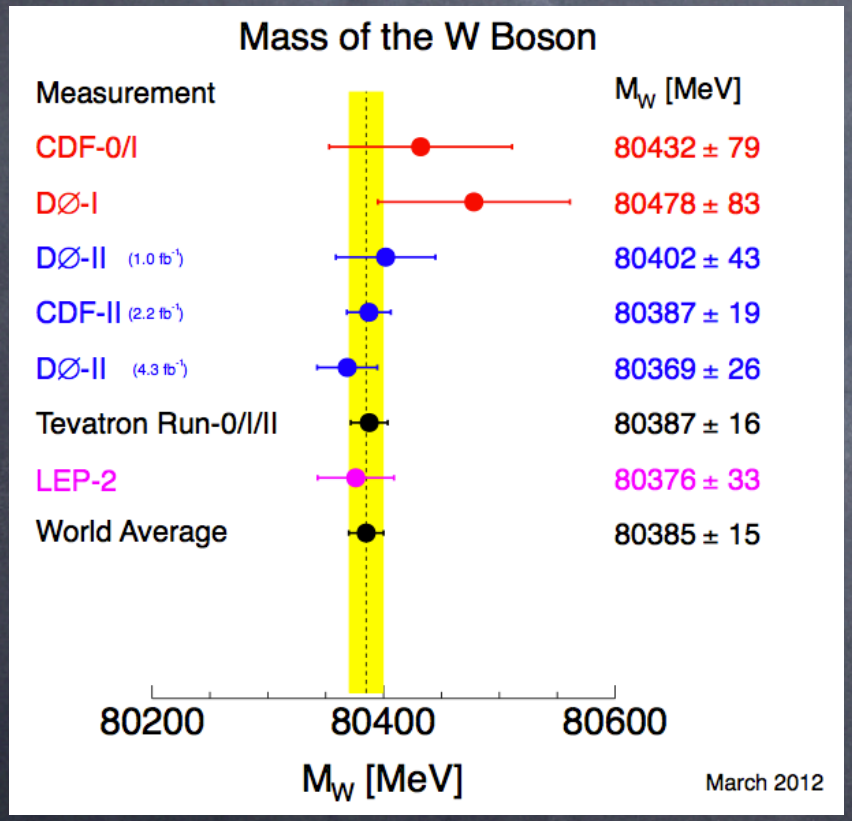
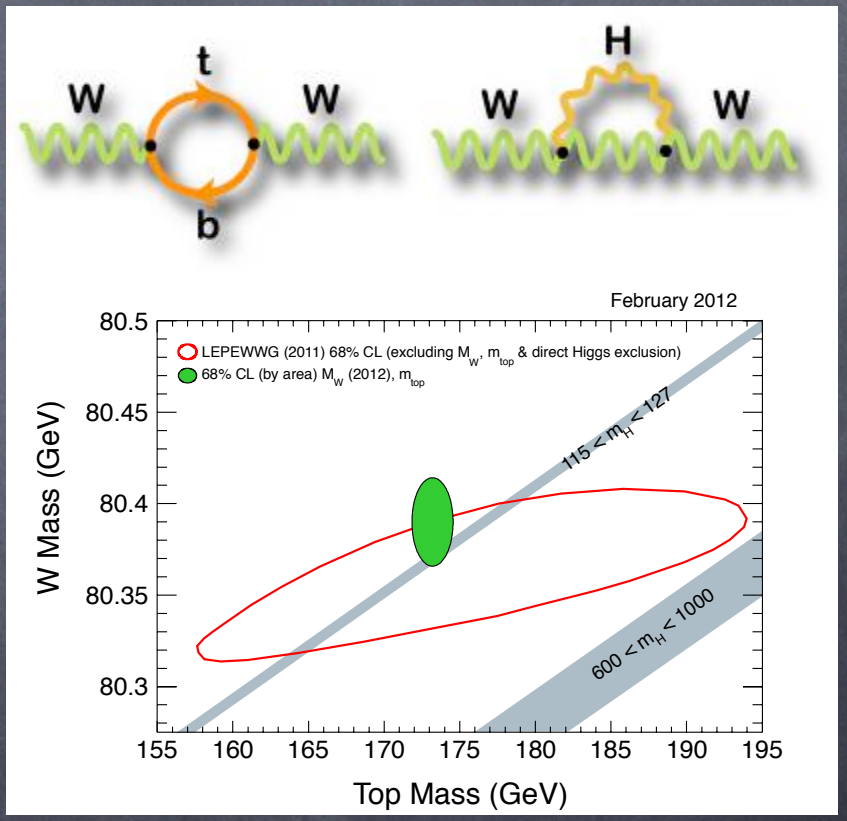
Fermilab
for the CDF Collaboration

incredible shrinking window

- improved limits from the LHC
- improved measurements in top mass and w mass
- provide strong motivation to focus on low-mass Higgs

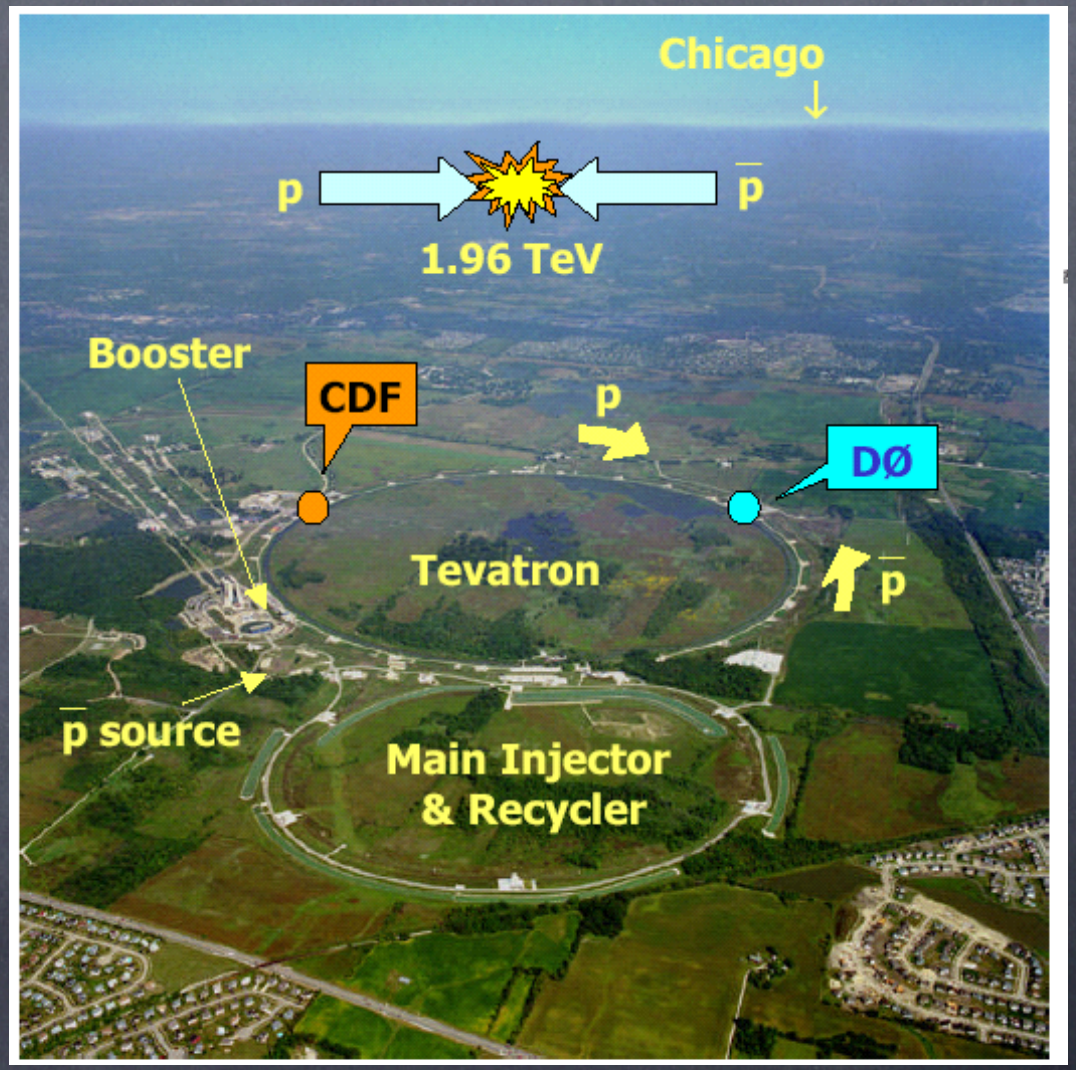




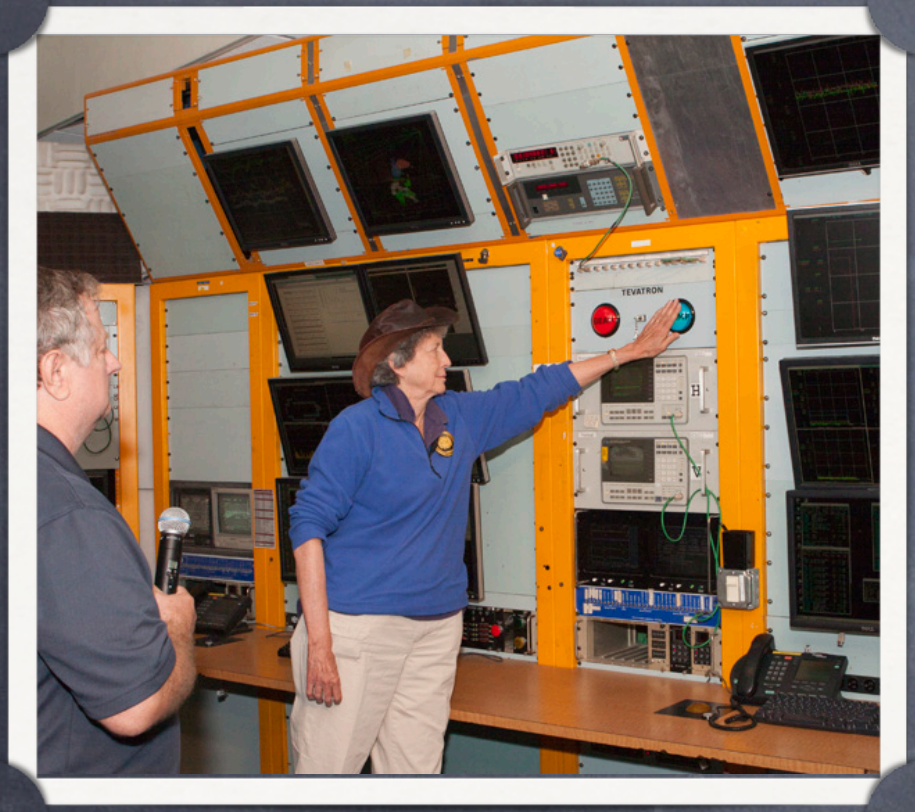
New World Average
$M_W = 80390 \pm 16$ MeV
CDF ± 19, DØ ± 23

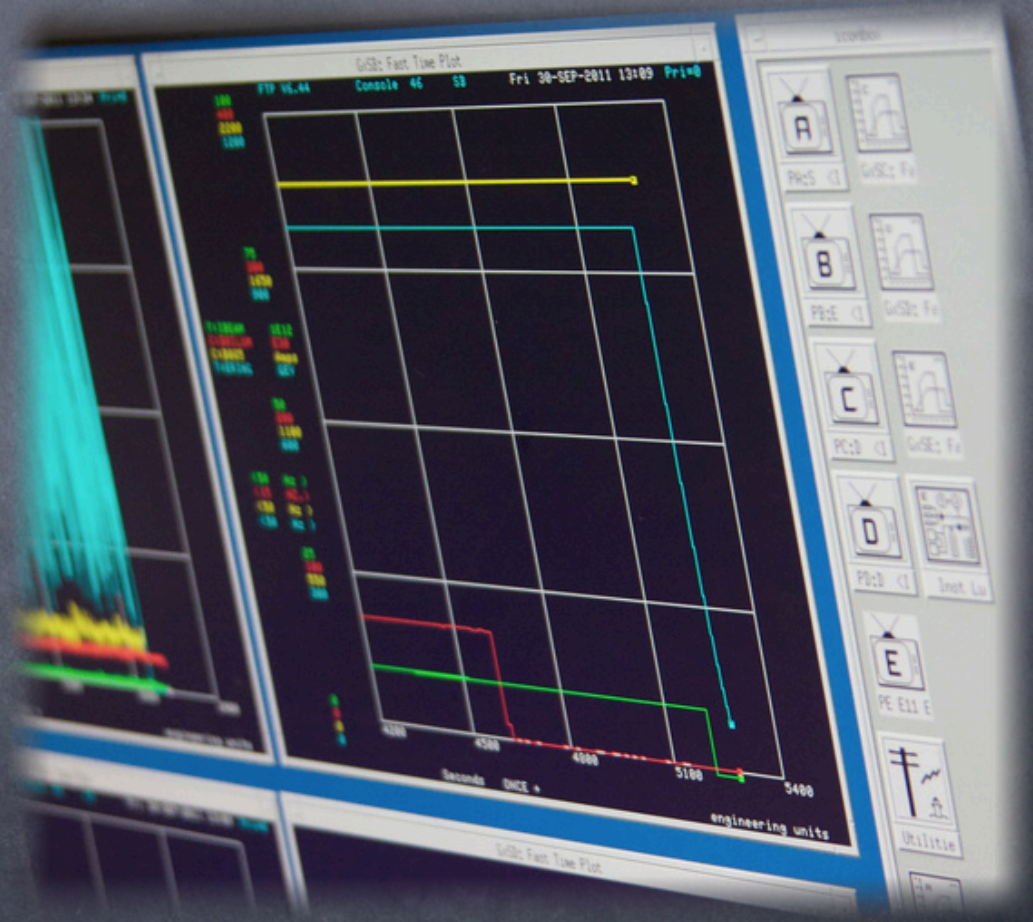
The Tevatron at Fermilab

- Tevatron proton-antiproton collider at Fermilab
  - $\sqrt{s}$ = 1.96 TeV
- EWK scale processes probe different region of parton distribution than LHC
- channel sensitivity differs from LHC



Tevatron Shutdown

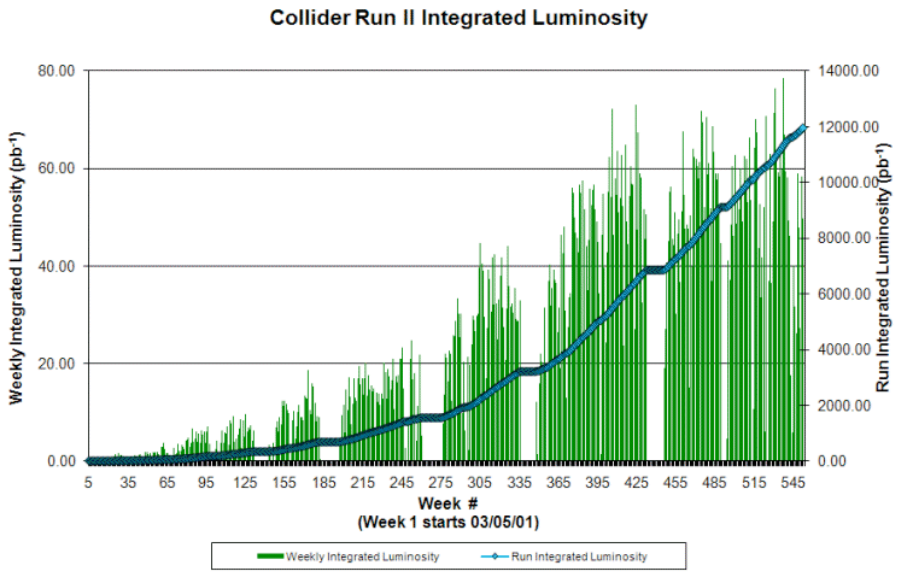


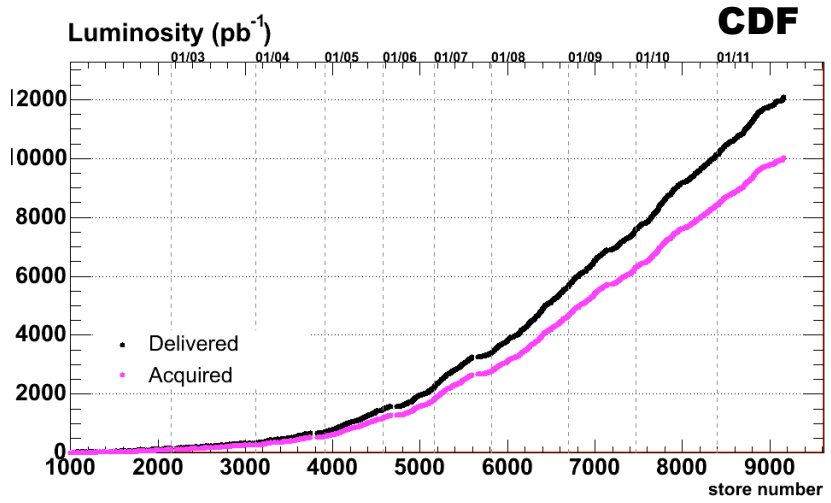


September 30, 2011

photo courtesy of Bodhitha Jayatilika

Tevatron Integrated Luminosity



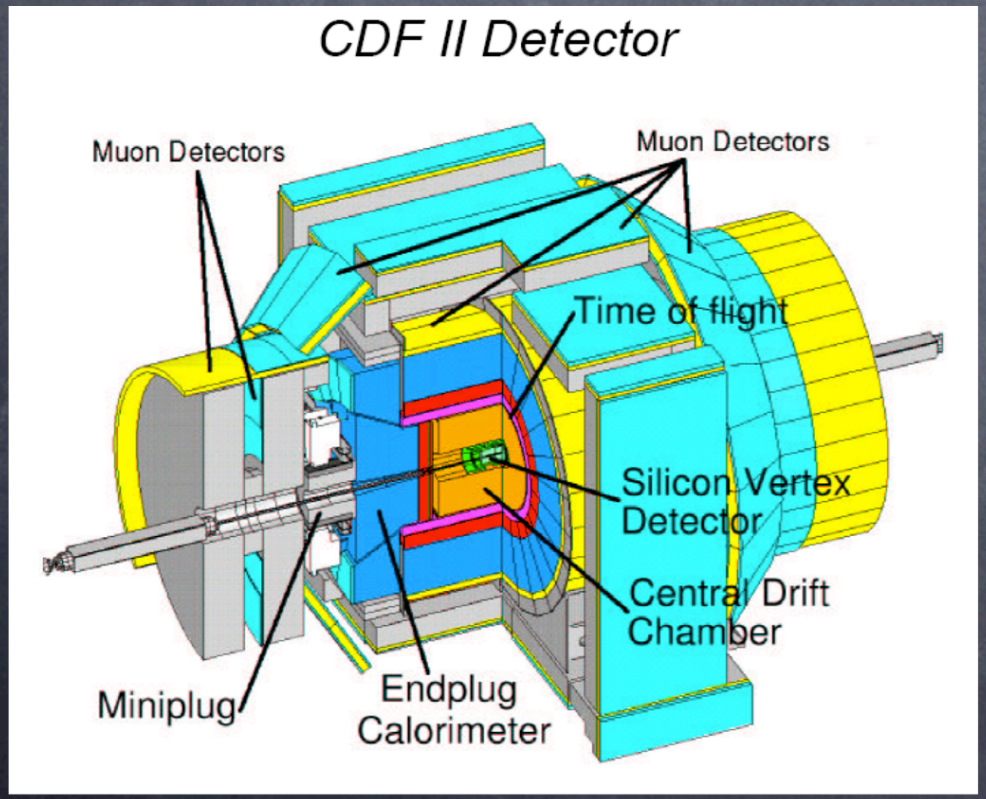


- delivered 11.9 fb^{-1}
- exceptionally efficient in final years

- recorded w/ ~90% eff
- final results ~10 fb^{-1}

CDF II detector

- **Spectrometer : Outer tracker and Silicon Tracker in 1.4 Telsa Solenoid**
- **Energy Flow : Fine segmented Calorimeter and Preshower (Steel/Iron and Scintillator)**
- **Muons : multi layer scintilator and drift chamber systems**
- **Hermetic : Excellent coverage of Tracking, Calorimeter and Muon Systems**



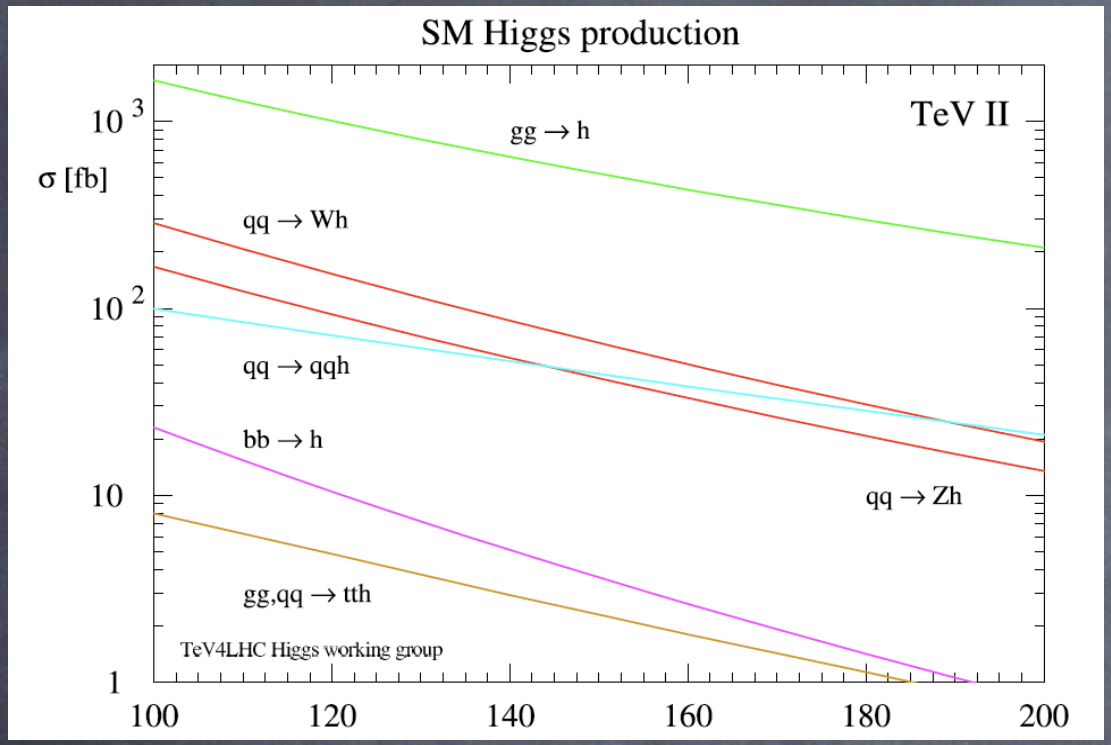
detector coverage

muons ~ 2

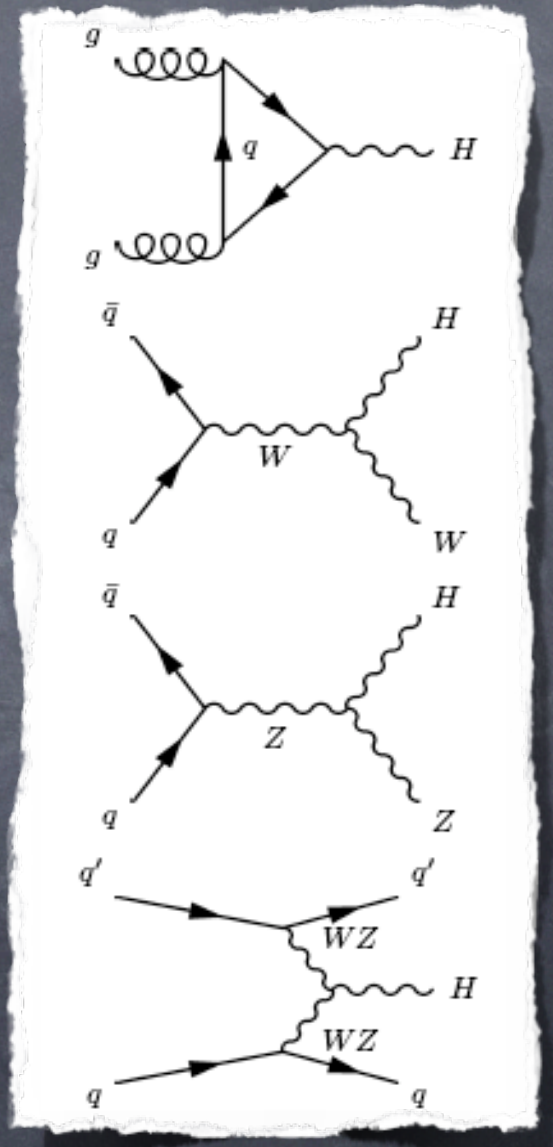
tracking ~ 2.5

EM/jet ~ 4

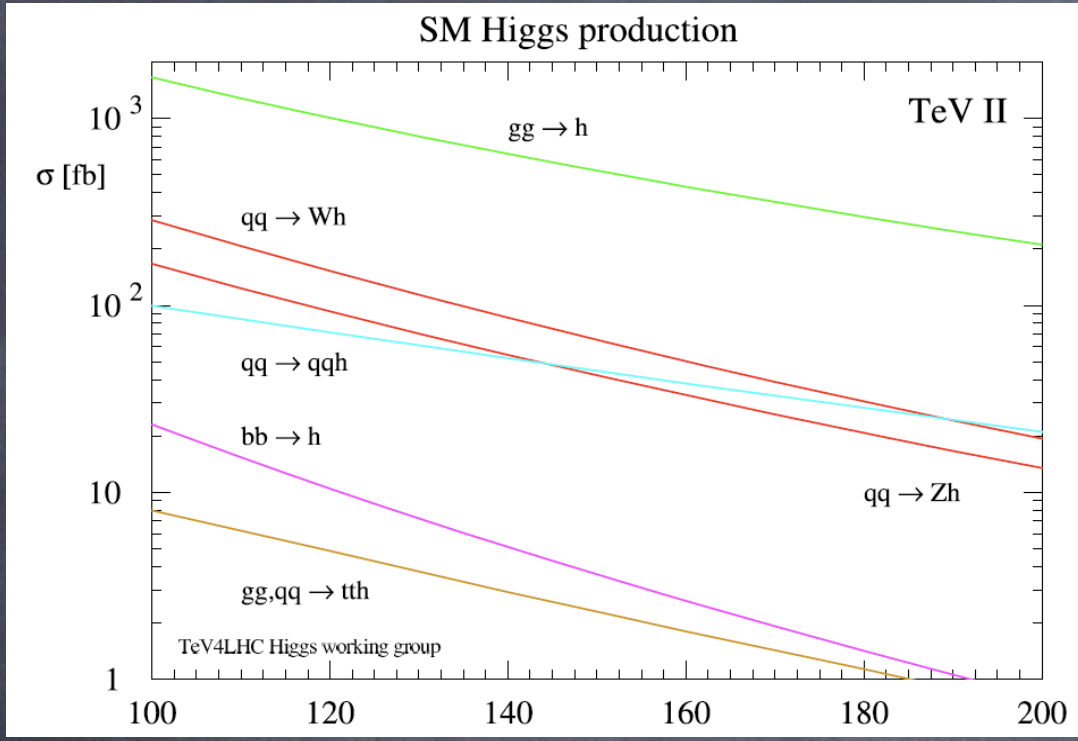
Higgs Production at Tevatron

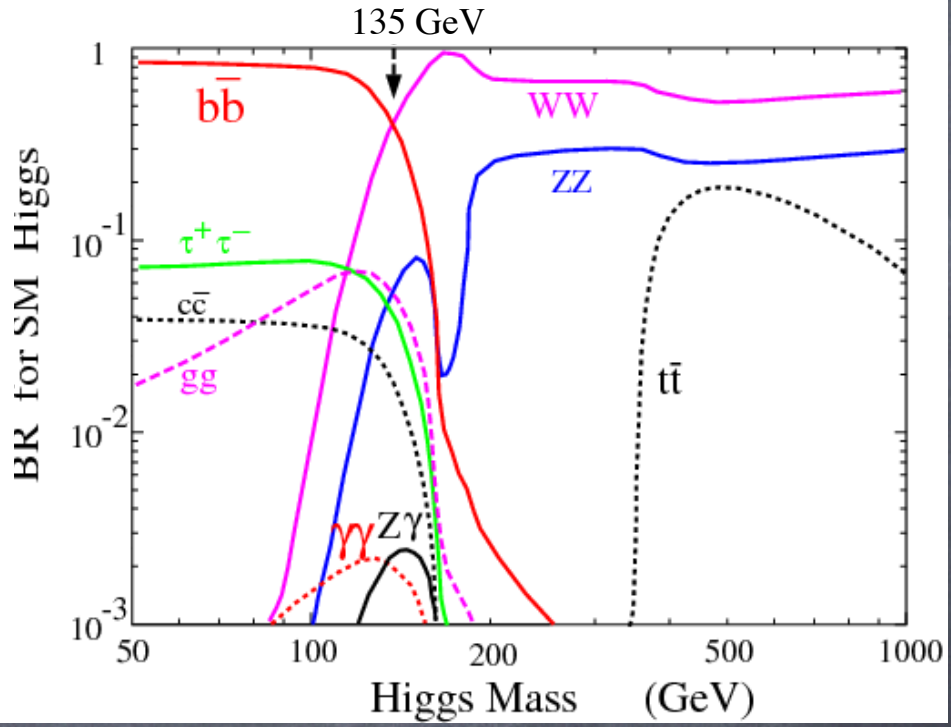


Gluon fusion dominates
Associated production (WH,ZH)
Vector Boson fusion



Higgs Production at Tevatron





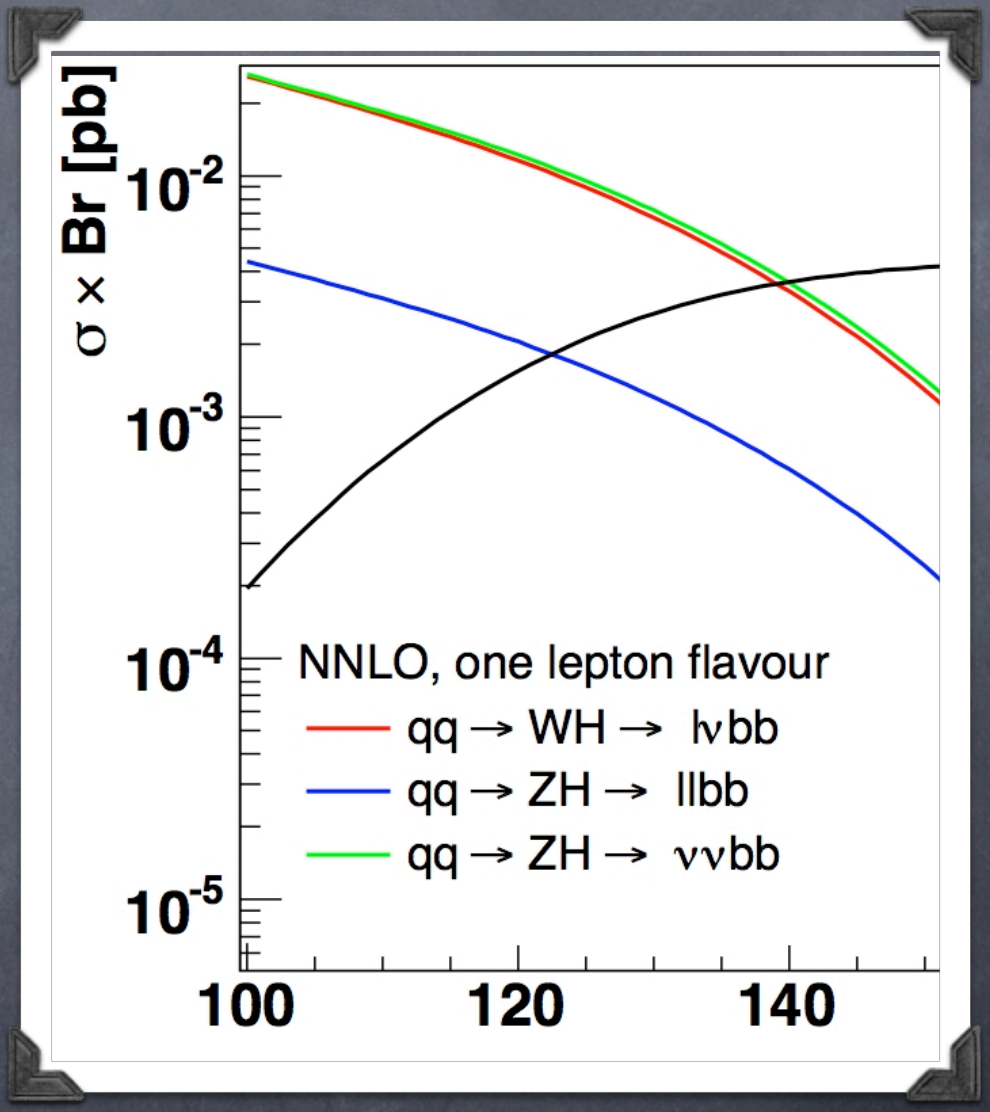
Gluon fusion dominates
Associated production (WH,ZH)
Vector Boson fusion

M_H<135, H→bb

M_H >135, H->WW

Higgs search at Tevatron

- focus on the low Higgs mass region
- re-evaluate current analysis tools to optimize signal acceptance
  - improve b-tagging strategy
  - jet energy resolution
  - develop new MVA discriminants
  - validation of search techniques in diboson measurements



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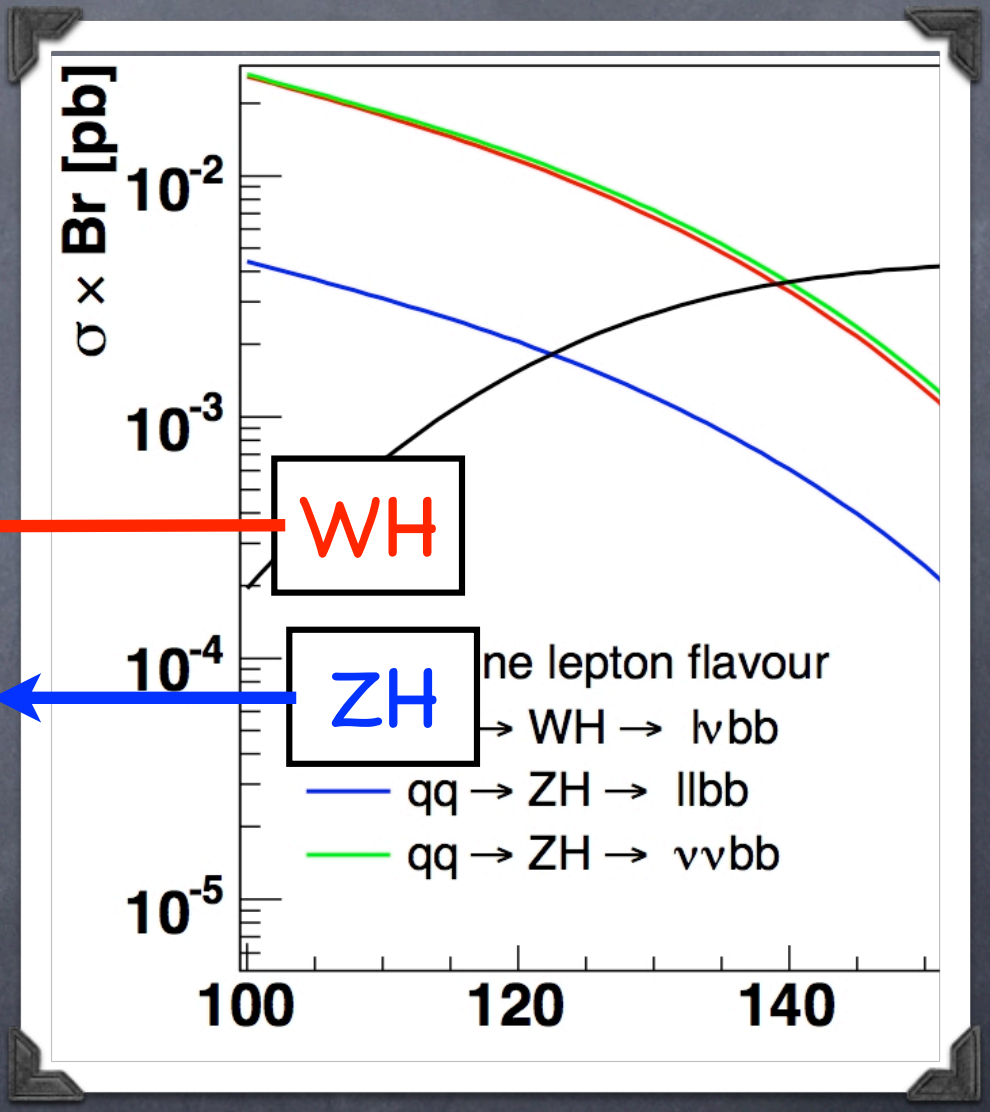
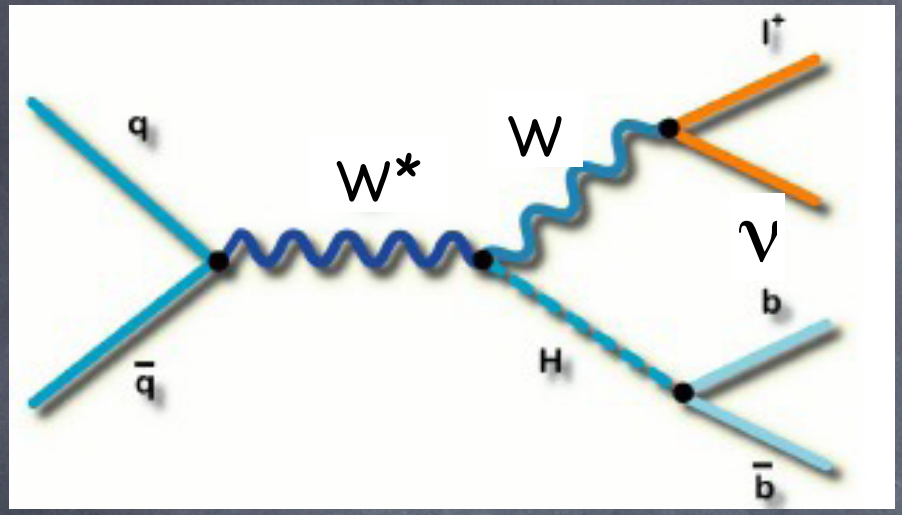
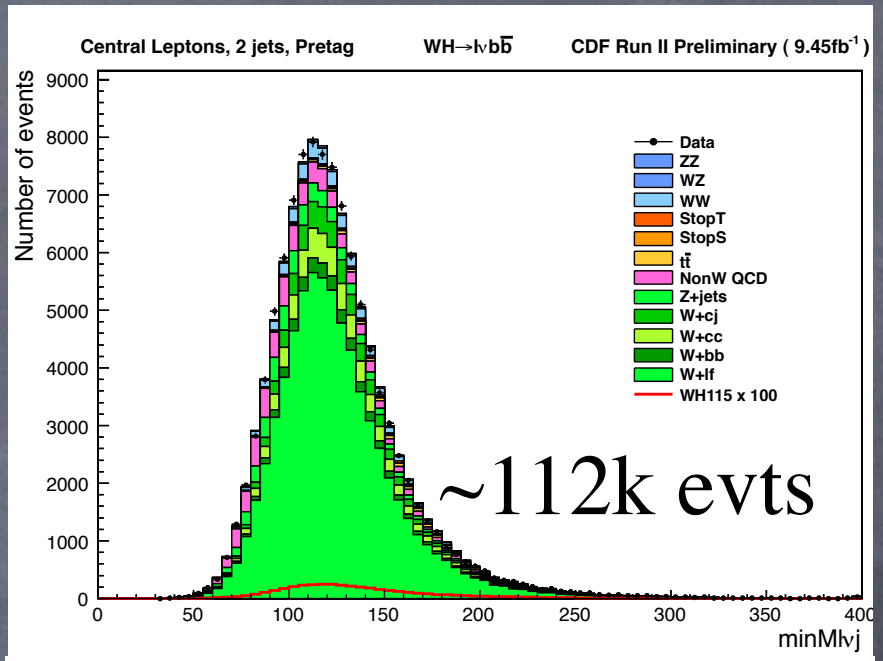
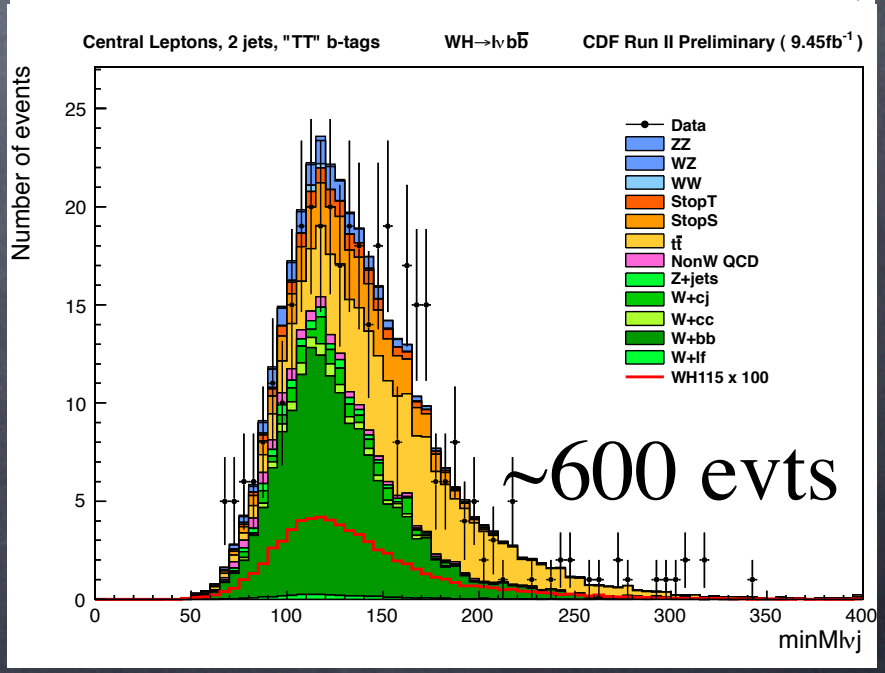


WH → *l*νbb Search

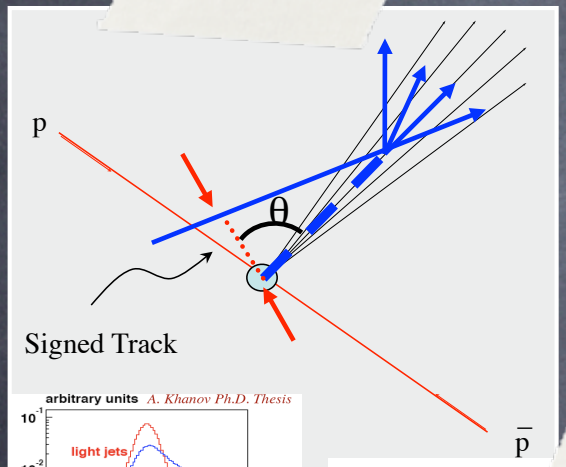


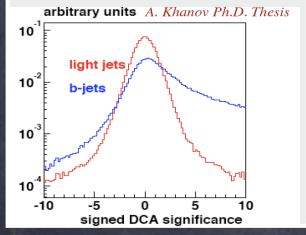


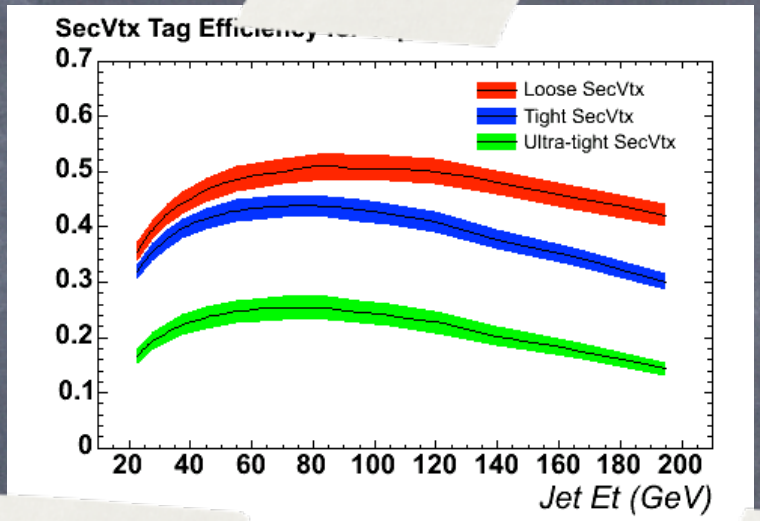


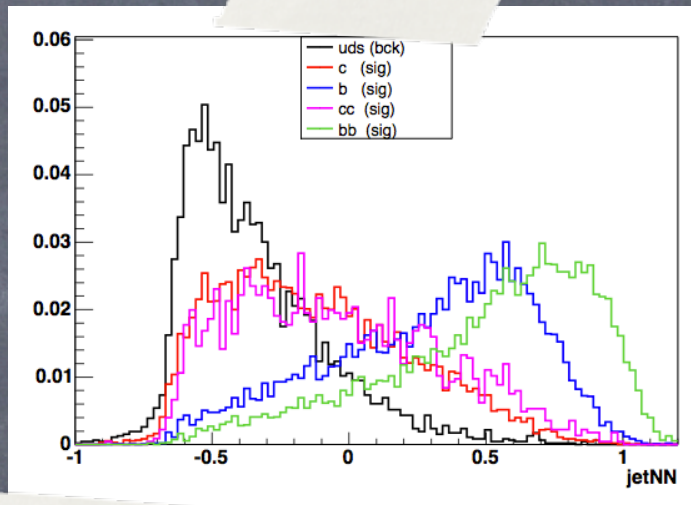
- Identification of b-quarks critical component
- Background rejection
- H→bb reconstruction

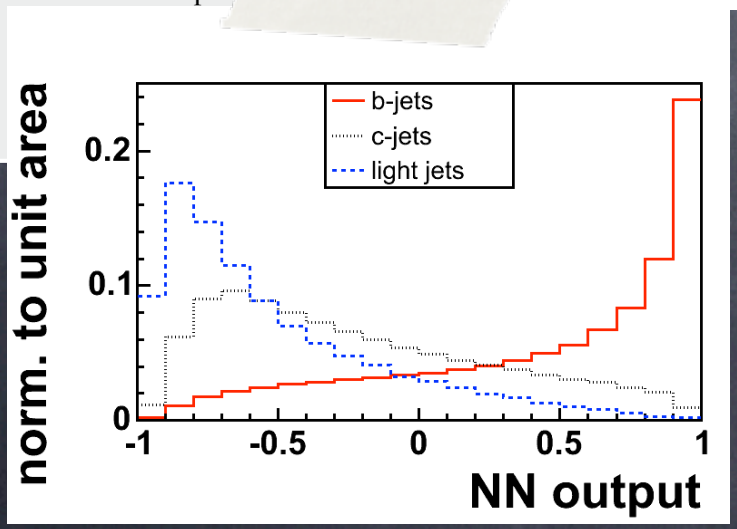
numerous b-taggers across several analyses

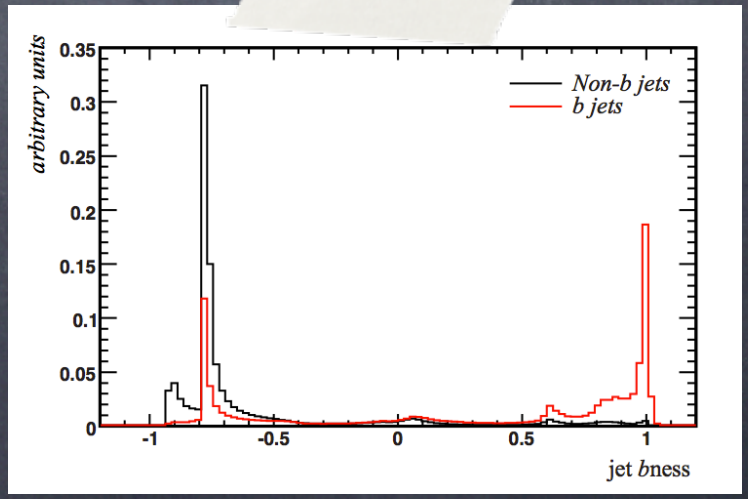










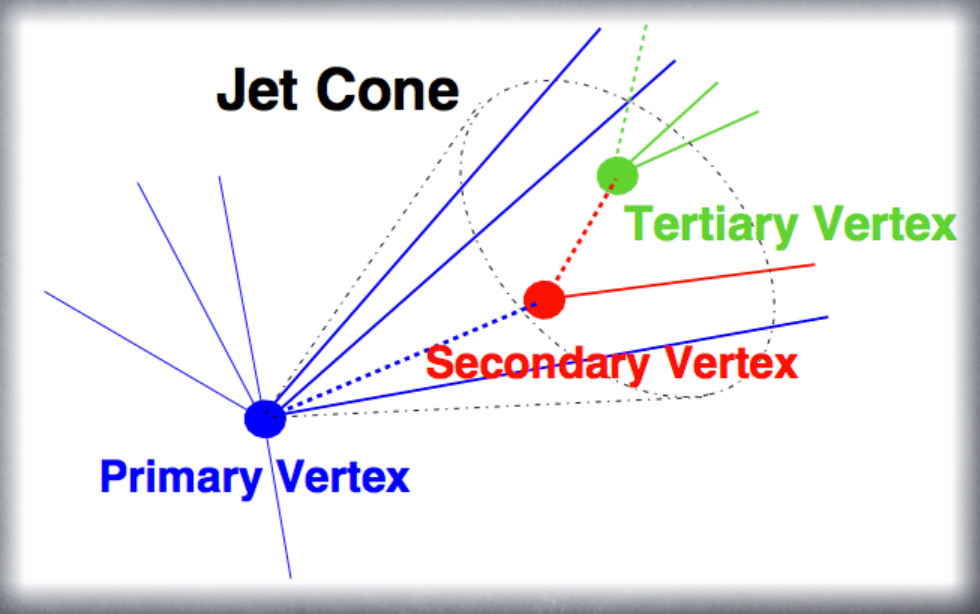


led to requirement for combined tagging channels

OLD – Multiple Taggers Tagging Category	S/√B
SecVtx+SecVtx	0.228
SecVtx+JetProb	0.160
SecVtx+Roma	0.103
Single SecVtx	0.146
Sum	**0.331**

identifying b-quark jets

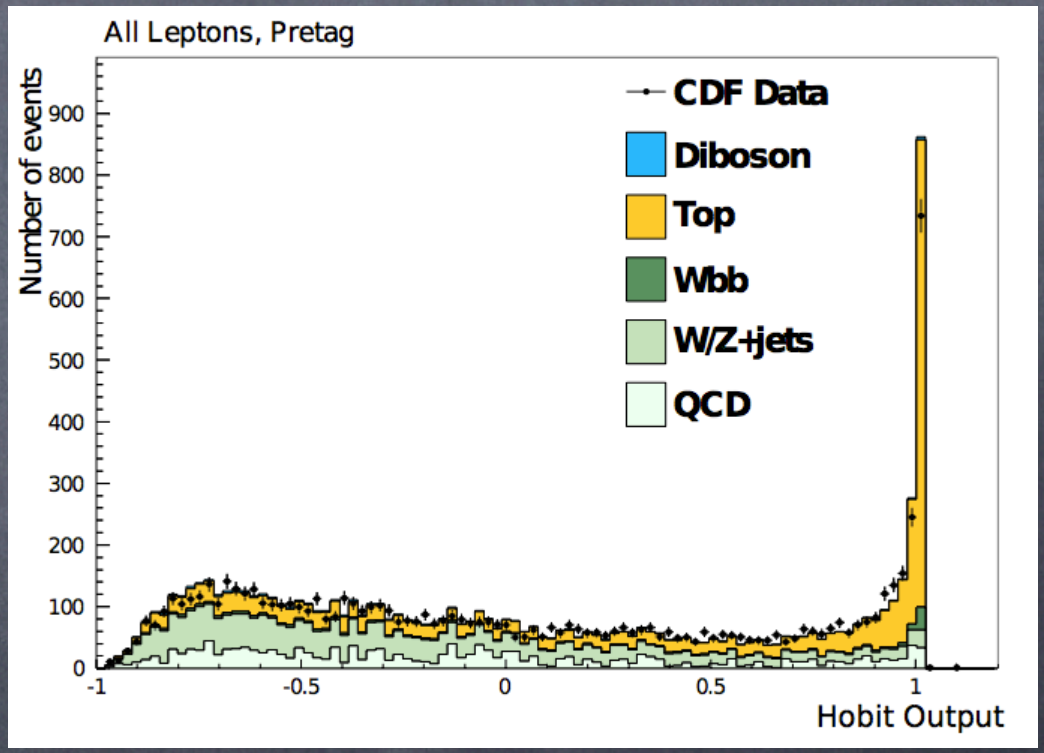
- previous taggers used in top quark, exotic, and qcd analyses
- utilize all features in single b-tagger
- displaced vertices
- high impact parameter single tracks
- soft charge muons from semi-leptonic decays



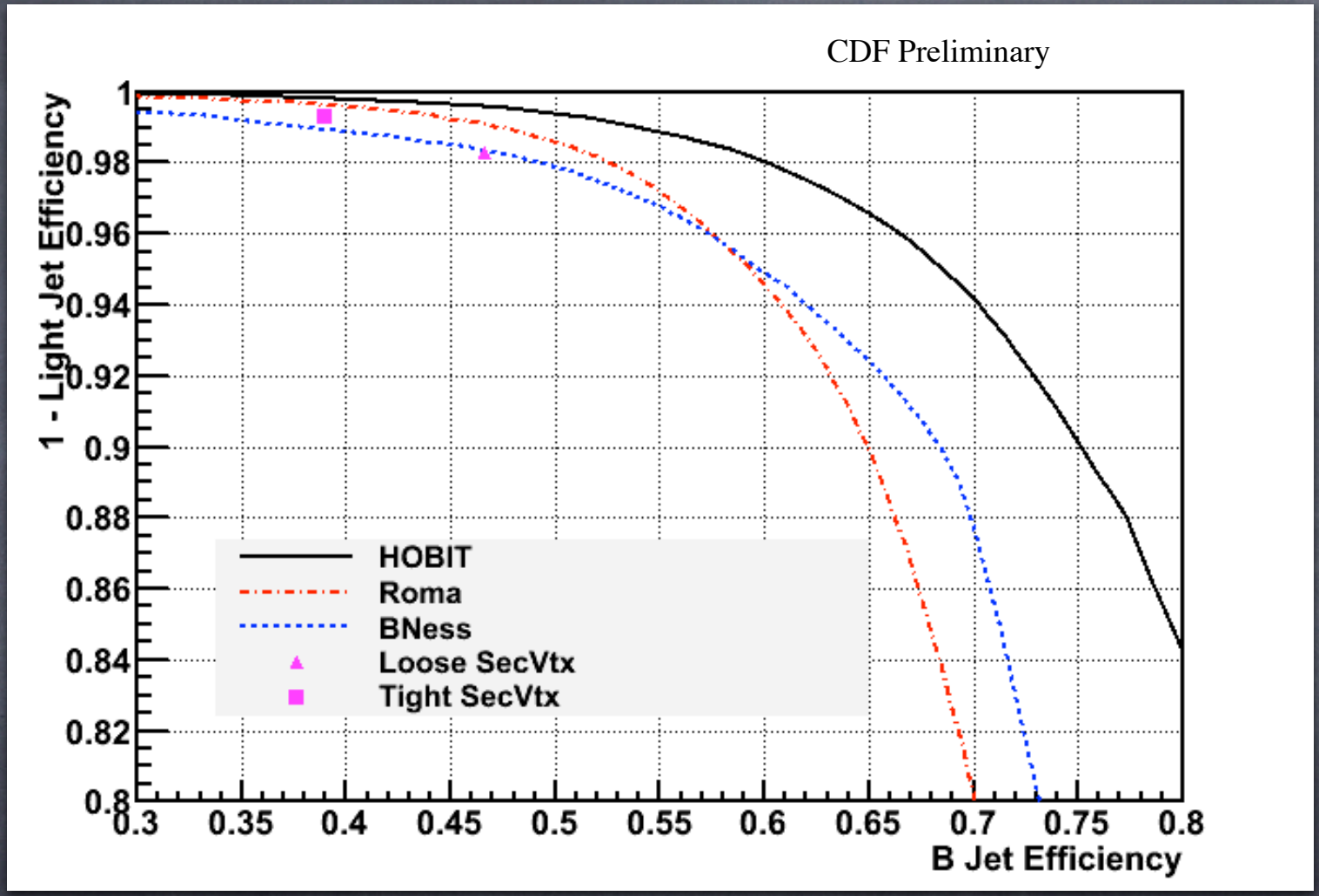
- optimize tagger for Higgs kinematic region and tagging thresholds

Higgs optimized b-identification tagger

- 25 input variables drawn from other taggers
- vertex: L3D, σ(L3D), vertex inv mass, pseudo-cτ,
- tracks: b-like track score (10), track multiplicity, track inv mass, total track p_T
- soft muon kinematics
- two operating points optimized for use in H→bb



HOBIT performance



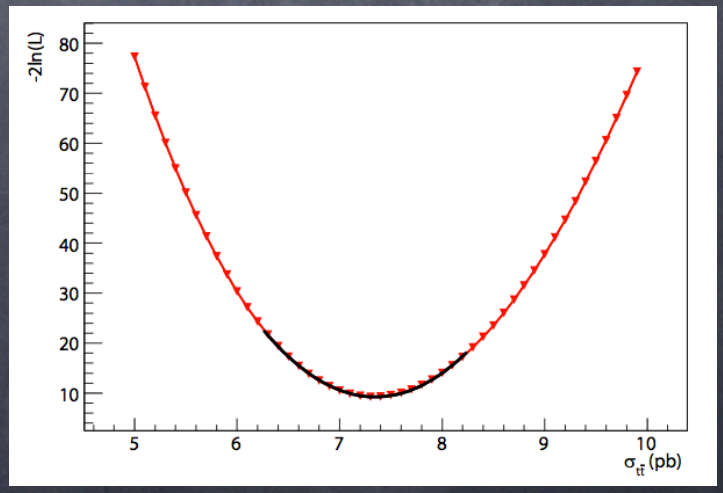
tagger	eff	HOBIT	increase
SV T	0.39	0.54	38%
SV L	0.47	0.59	25%

HOBIT validation

- compare performance in simulation with data
- previous taggers utilized resolution effects to measure corrections
- no longer available in MVA tagger, but now have large orthogonal datasets
- measure correction scale factors using two techniques
- combine the two measurements to reduce the b-tag efficiency uncertainty

σ(tt) method

- previously measure σ(tt) and b-tag eff simultaneously
- select tt-bar enhanced data
  - W+3,4,5+ jet sample with large H_T
  - W+1 jet sample
- fluctuate the b-tag eff and light-jet mistag efficiency
- perform 2D χ^2 minimization in b-eff SF and mistag SF

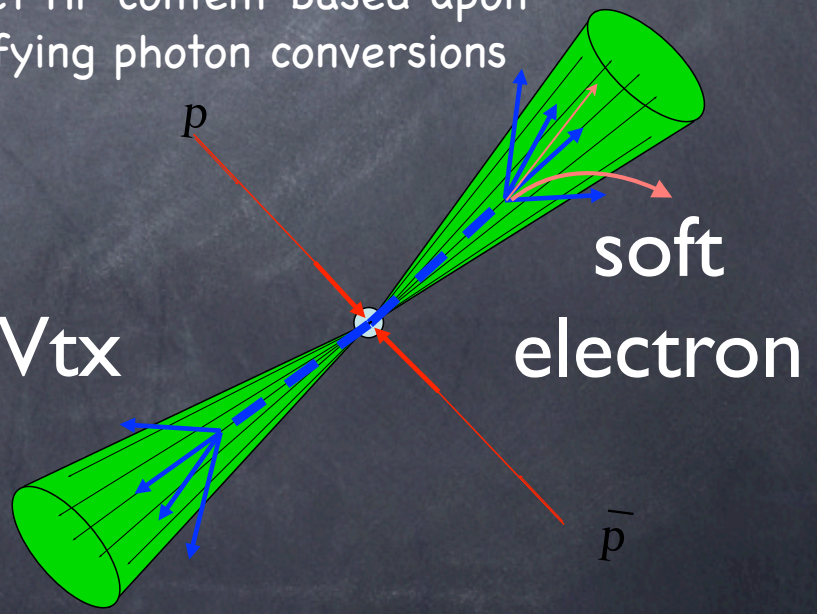


HOBIT validation

- compare performance in simulation with data
- previous taggers utilized resolution effects to measure corrections
- no longer available in MVA tagger, but now how large orthogonal datasets
- measure correction scale factors using two newly developed techniques
- combine the two measurements to reduce the b-tag efficiency uncertainty

soft-electron method

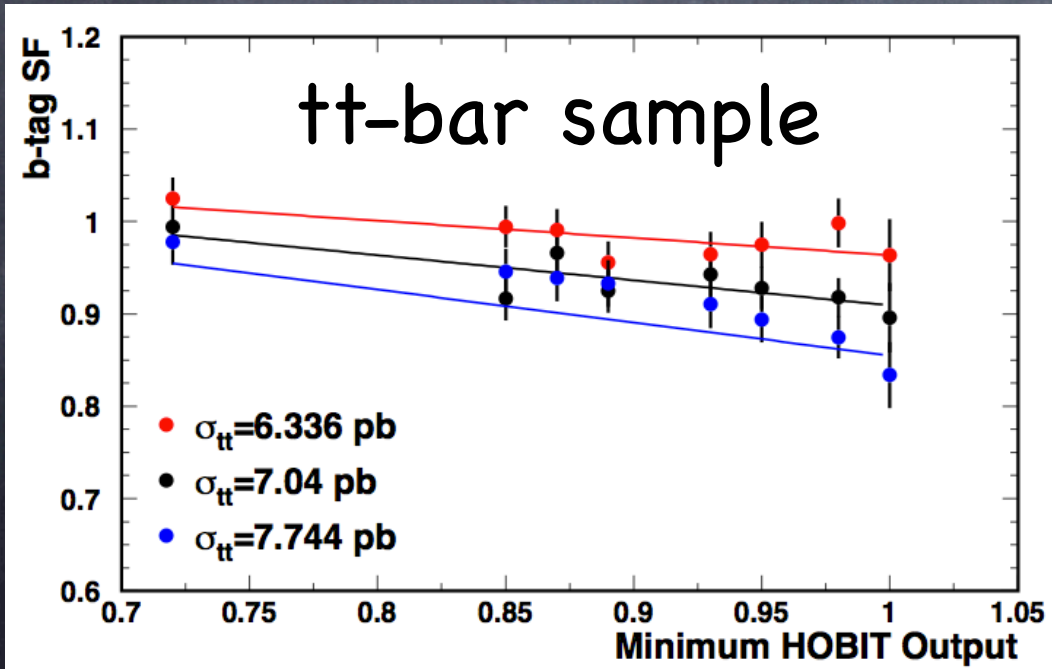
- use known efficiency of SecVtx tagger to generate tag-probe sample
- enhance b-content in the probe jets with soft-electron tagging
  - all variables orthogonal to HOBIT inputs
- correct HF content based upon identifying photon conversions

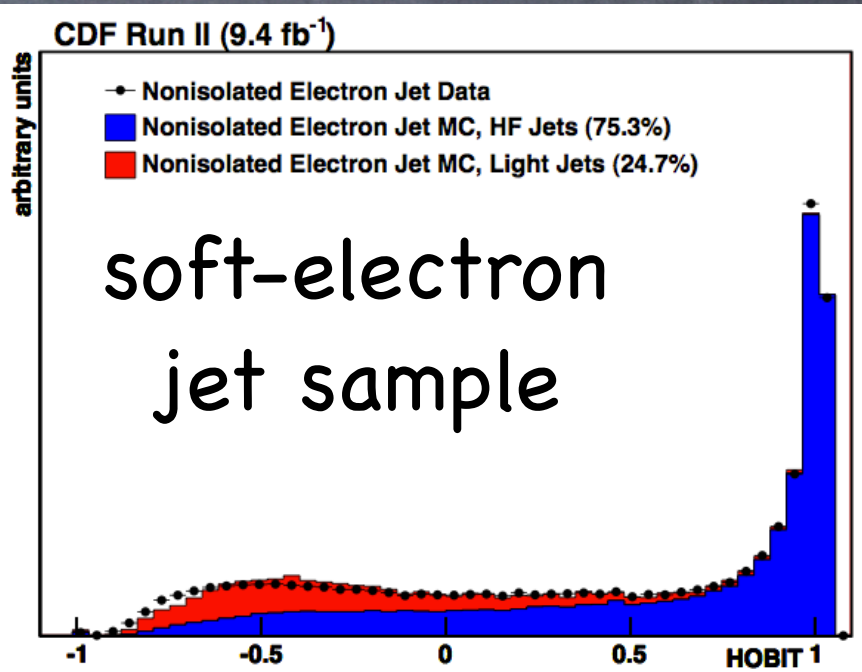


HOBIT validation

- combine the two measurements to reduce the b-tag efficiency uncertainty
- give access to full kinematic range of jets from tt-bar and dijet events

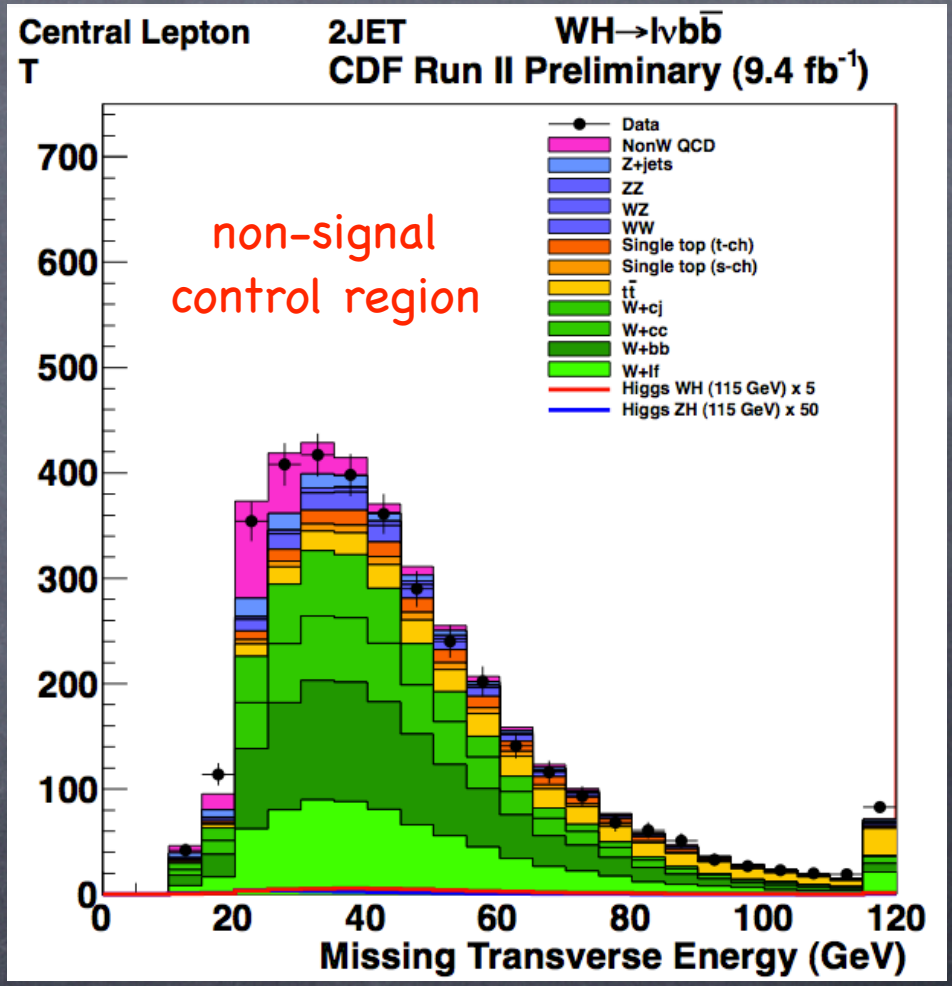
HOBIT	eff SF	uncert
tight	0.993	±0.032
loose	0.937	±0.037





HOBIT in low-mass Higgs

- excellent agreement in HOBIT tagged samples
  - single Tight tag control
- HOBIT has been incorporated into most CDF low-mass analyses
- each analysis optimized operating points for best signal to background
  - use Tight and Loose points
  - up to 5 tag categories TT, TL, Tx, LL, Lx



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SecVtx+Roma	0.103
Single SecVtx	0.146
Sum	**0.331**

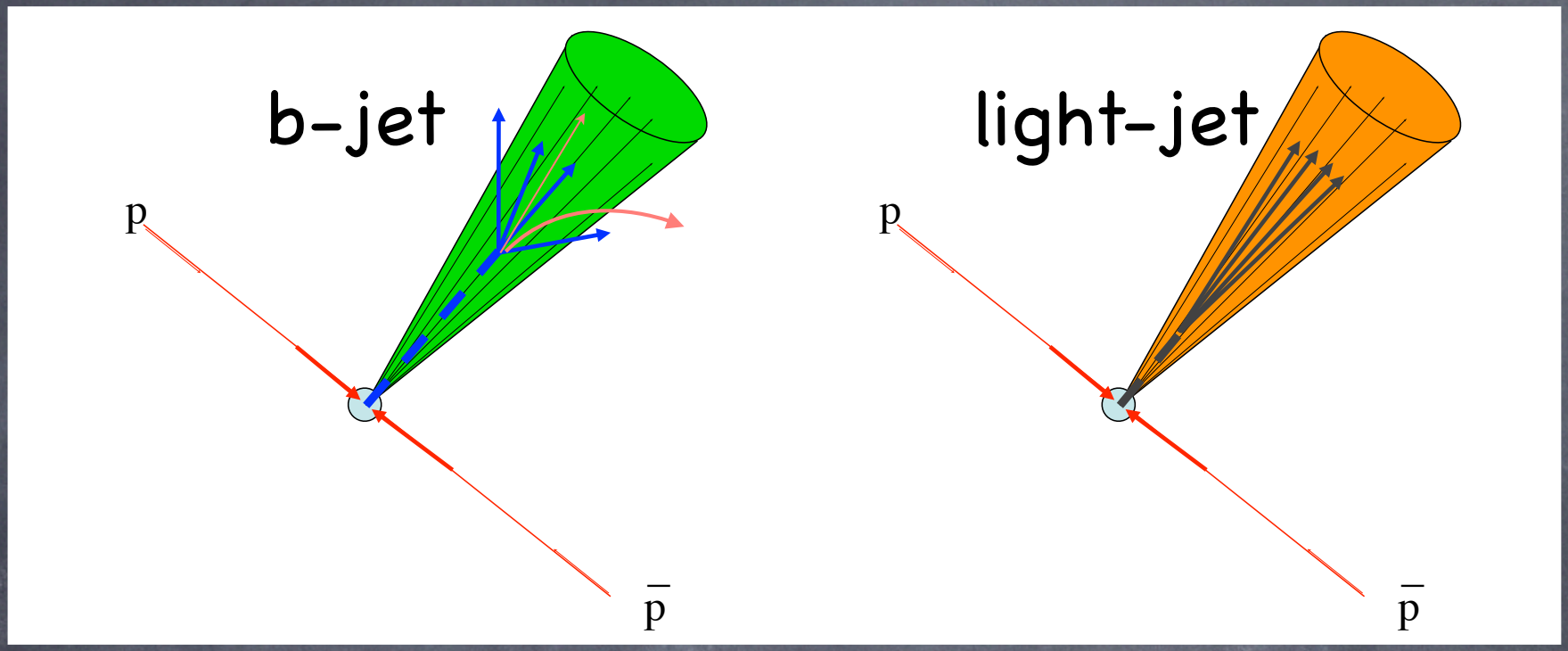
New Hobbit Tagging Category	S/√B
Tight-Tight	0.266
Tight-Loose	0.200
Single Tight	0.143
Loose-Loose	0.053
Single Loose	0.044
Sum	**0.369**

Tag Category	b-jet eff	light jet fake
Tight	42%	0.89%
Loose	70%	8.9%

increase > 10% in S/√B for WH→lνbb

increase > 15% in S/√B for ZH→llbb

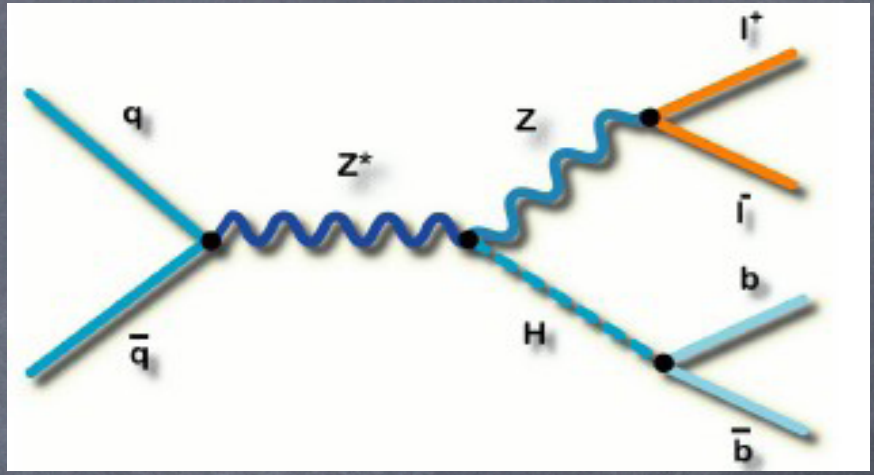
jet energy resolution

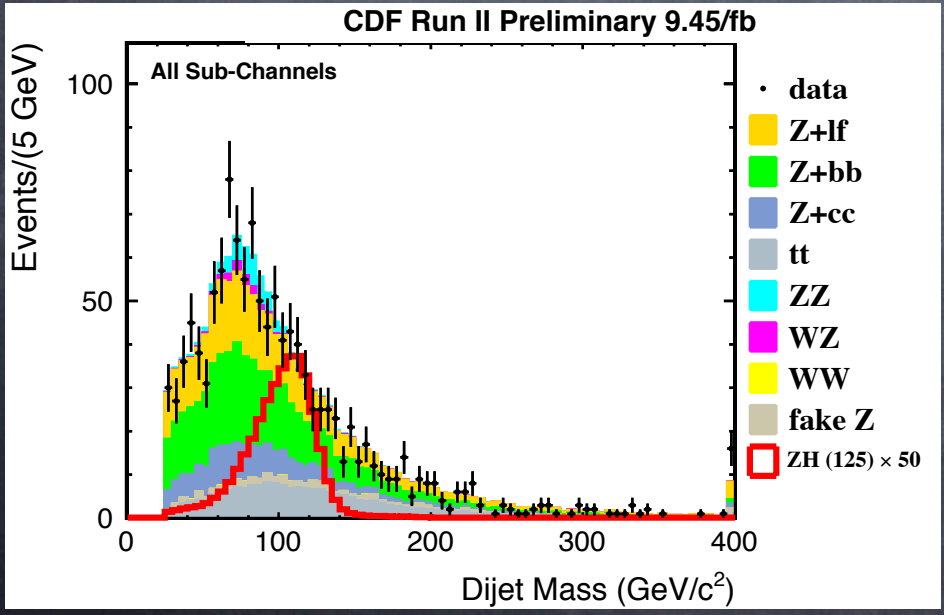


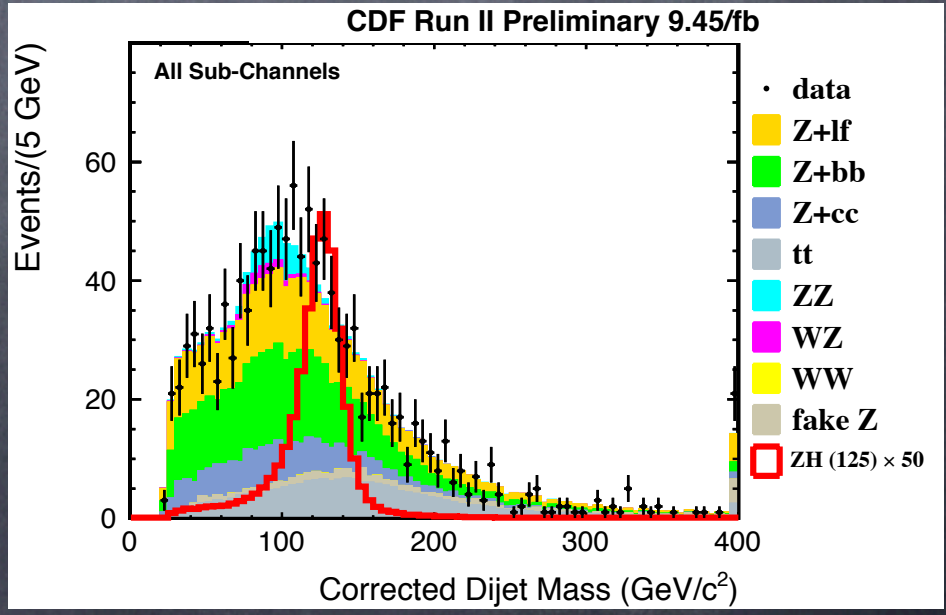
- b-jet calorimeter deposits have sizable differences from light-jets
- develop specialized NN and corrections for b-jets to improve H→bb mass resolution

ZH → *ll*bb Signature

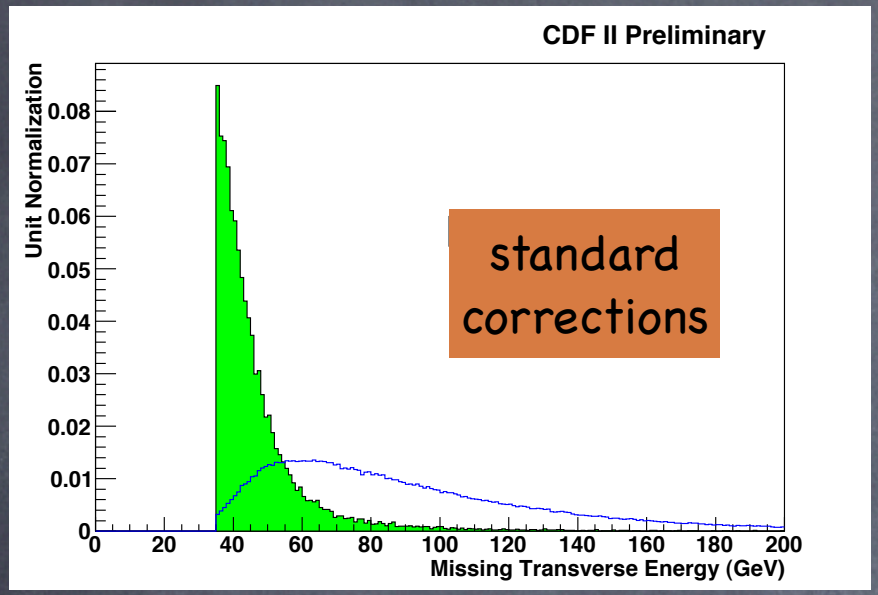
- lepton E_T resolution is excellent and provides constraint
- attribute missing-E_T to measurement of jets
- trained Neural Network to balance jets against missing-E_T

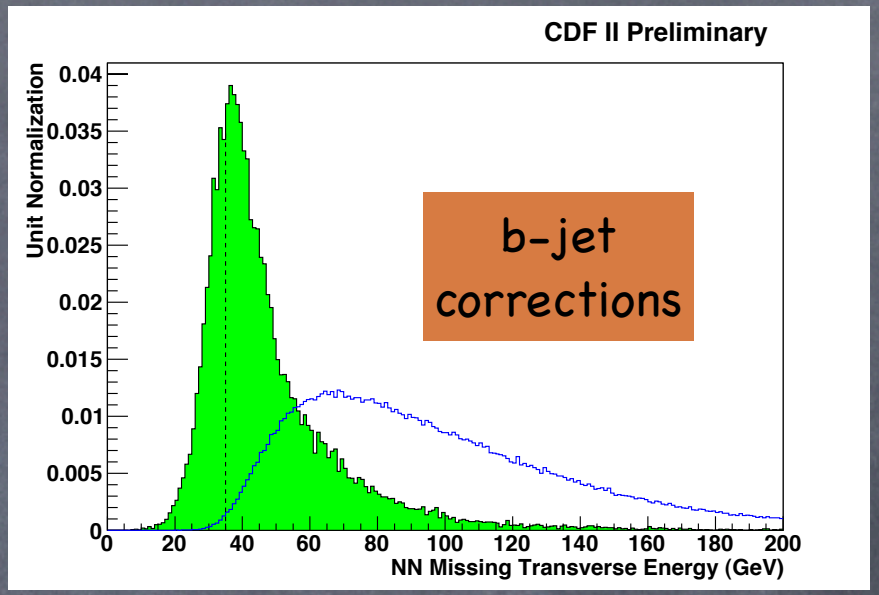




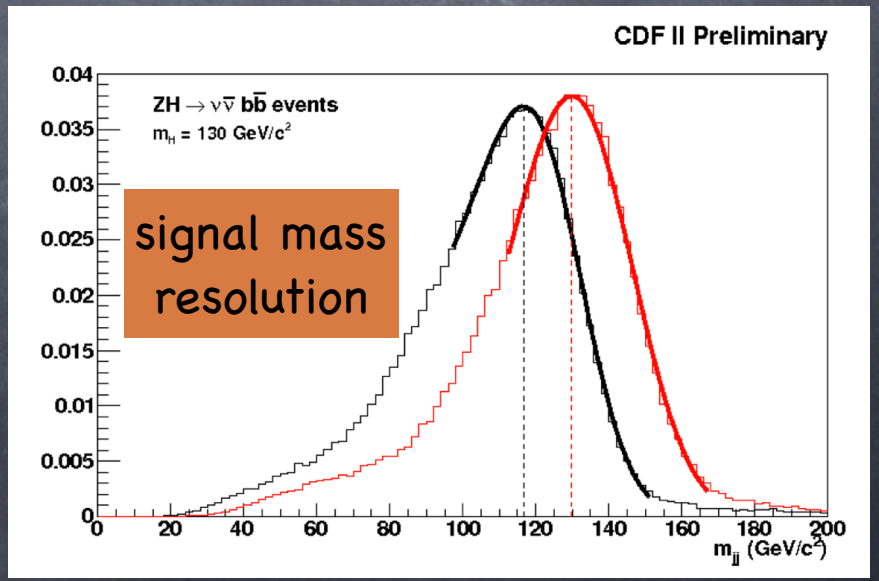


ZH → $\nu\nu$bb Signature



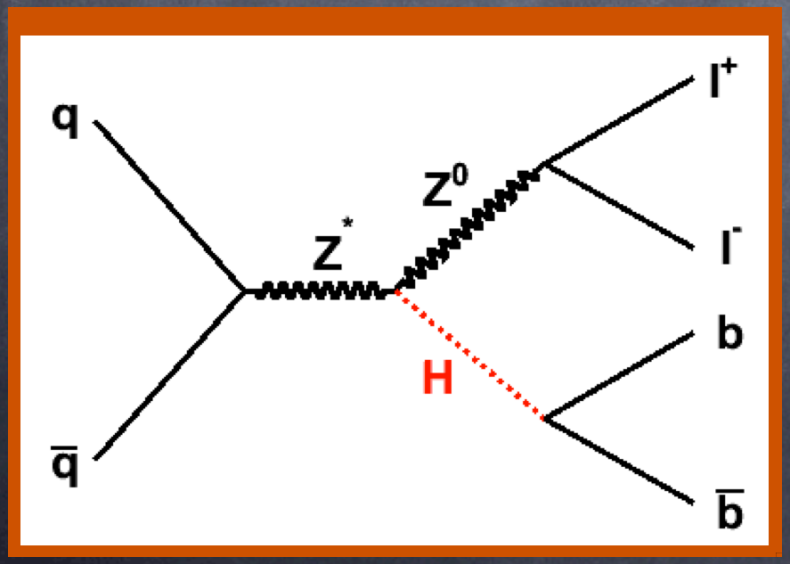


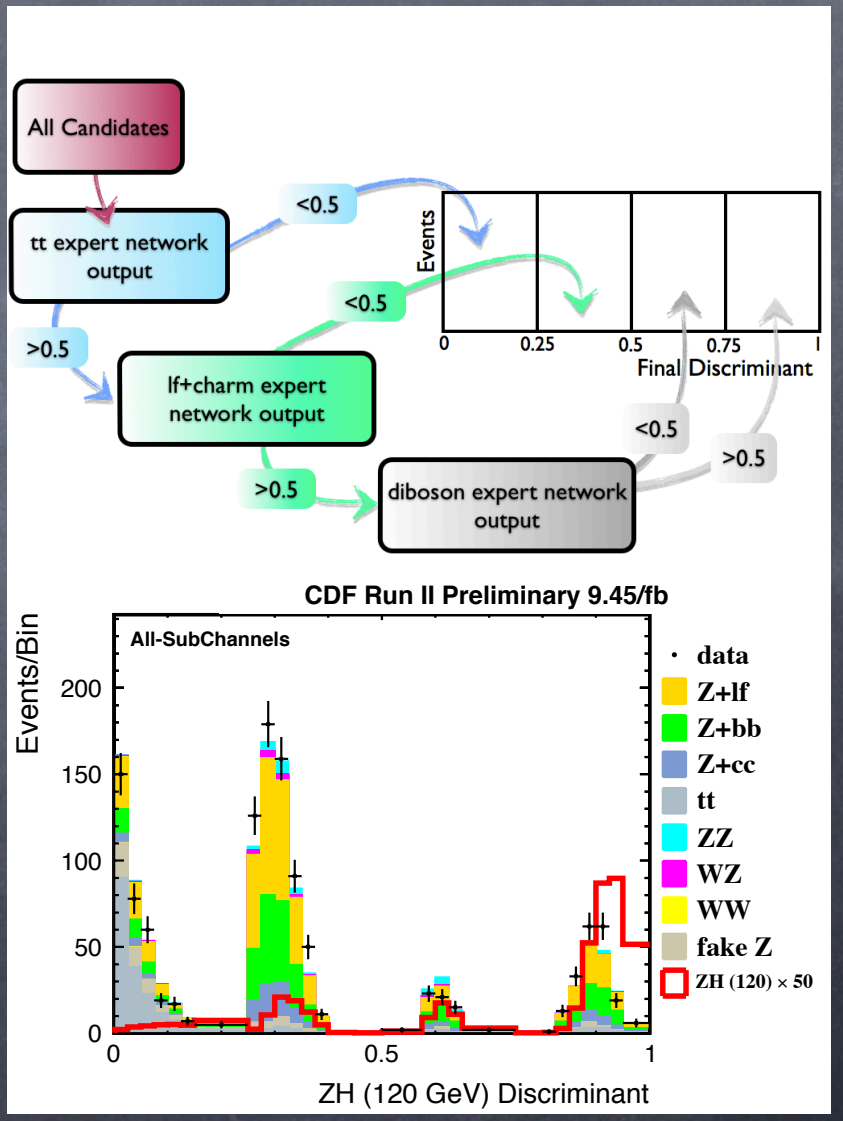
- NN based b-jet corrections
- better signal/background separation
- RMS/mean improves in Met+bb
  - 0.195 -> 0.156
- b-jet corrections now included in all H→bb analysis



multivariate methods

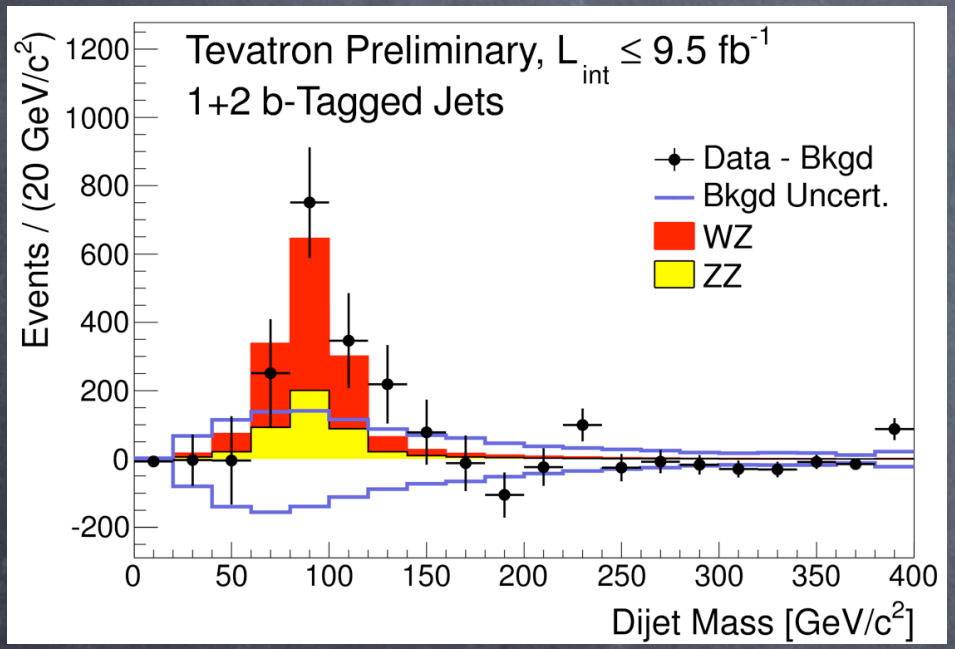
- develop MVA for specific backgrounds
- multi-stage classification of events
- separate easiest background first
- train final discriminant after

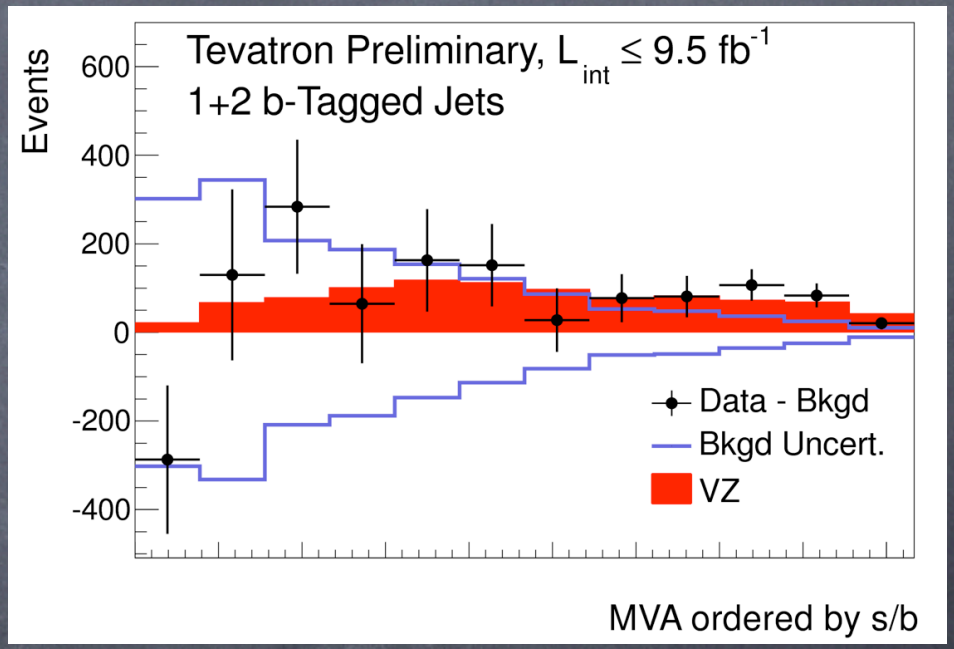




search for WZ/ZZ→X+bb

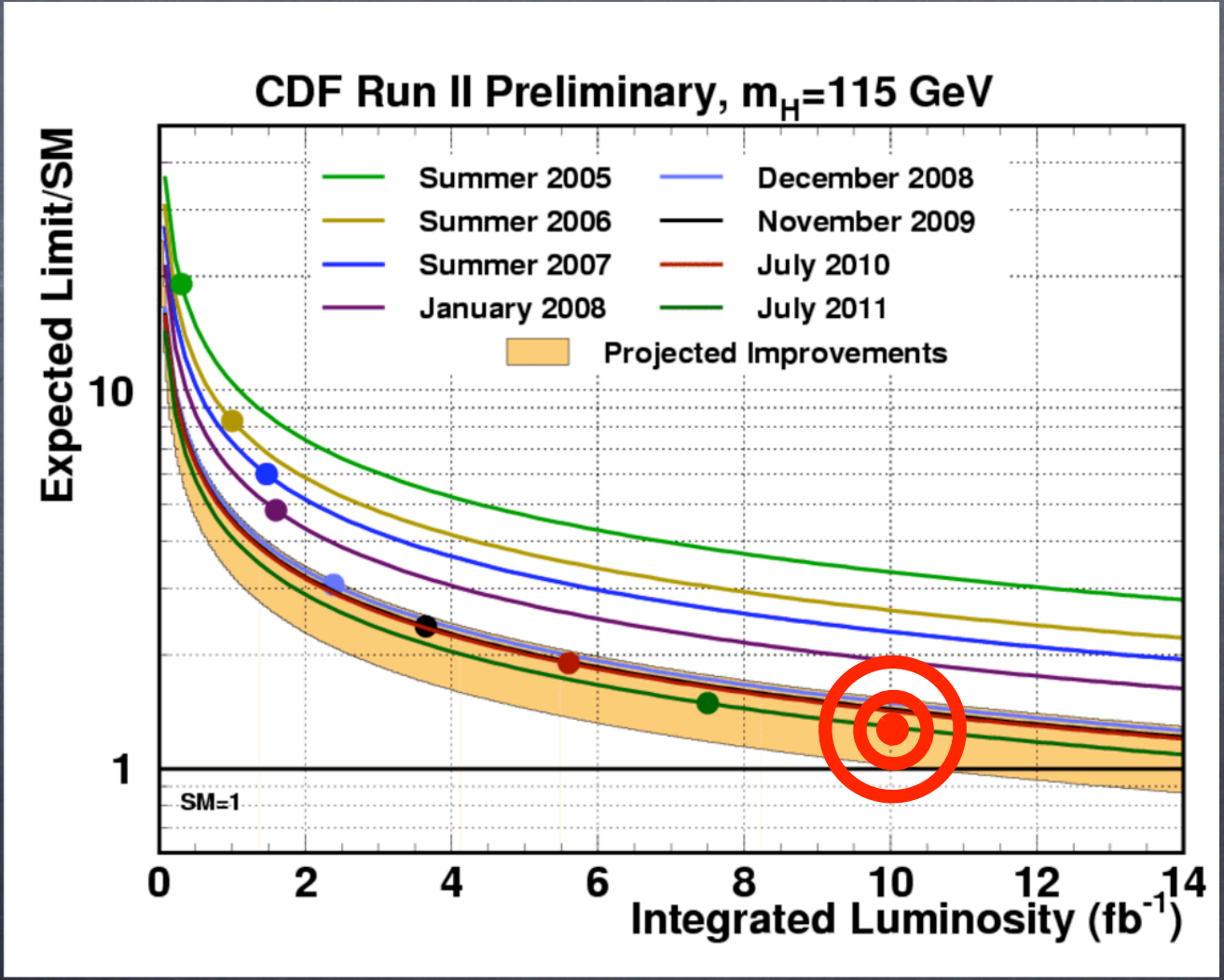
- identical final state as WH/ZH→X+bb
- $\sigma(VZ) \approx 5x\ \sigma_{SM}(VH)$
- use same search strategy
- critical test of analysis





$\sigma(VZ) = 4.47 \pm 0.64_{(stat)} \pm 0.73_{(syst)}$ pb
approximately 4.6σ significance
$\sigma_{SM}(VZ) = 4.4 \pm 0.3$ pb

Expected CDF Sensitivity



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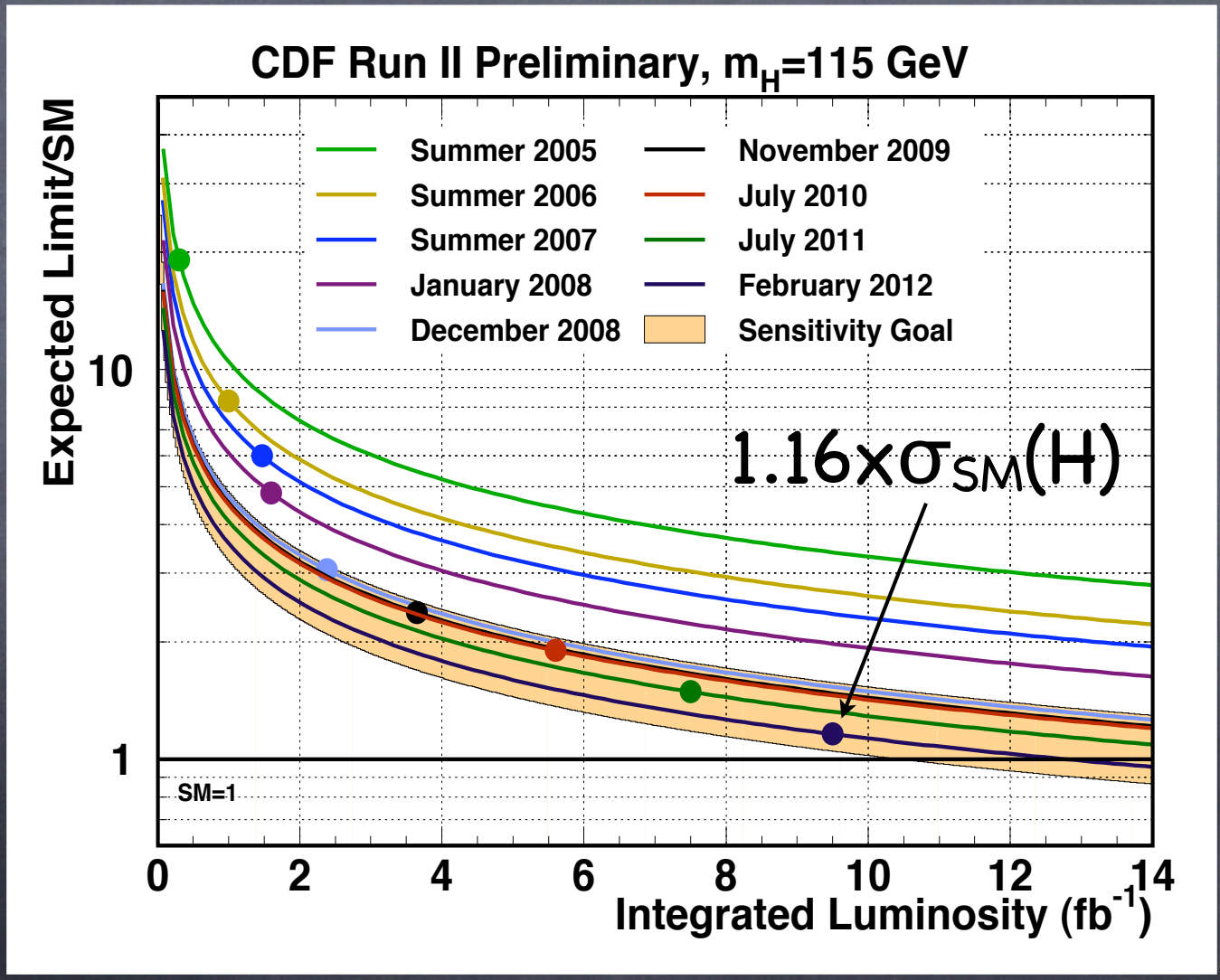
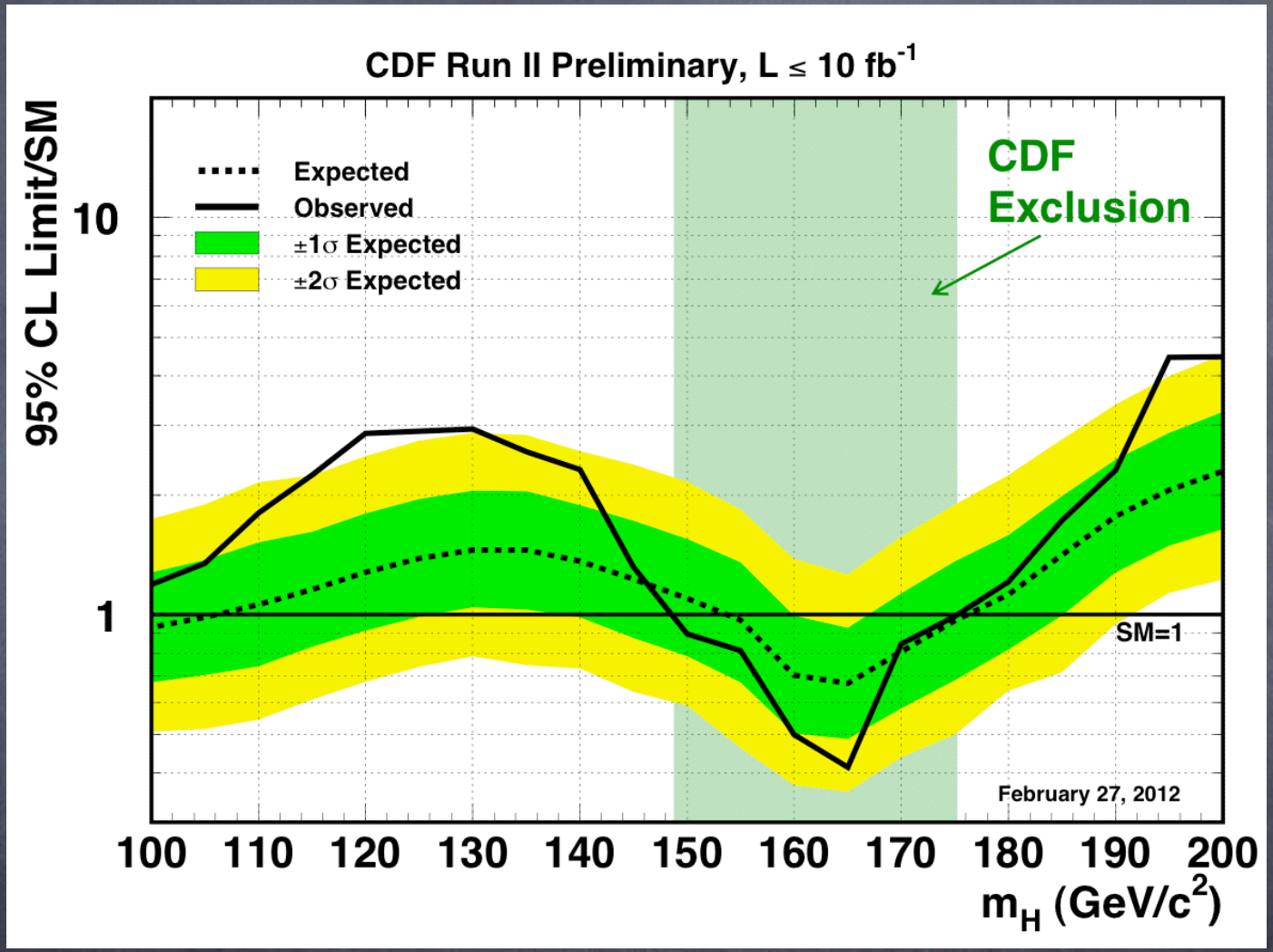


CDF Full Combination

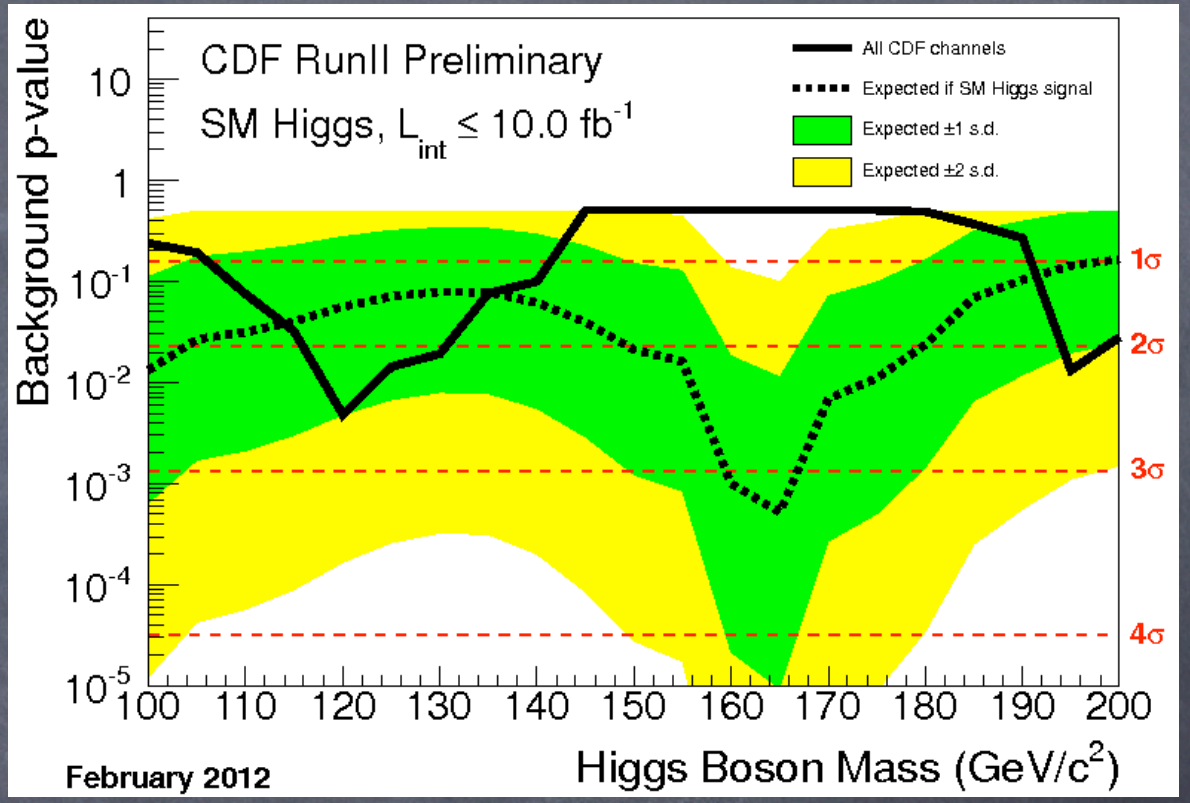


Exclude SM Higgs at 95% C.L. : $147 < m_H < 175$ GeV/c^2

Expect to exclude: $100 < m_H < 106$ GeV/c^2 & $154 < m_H < 176$ GeV/c^2

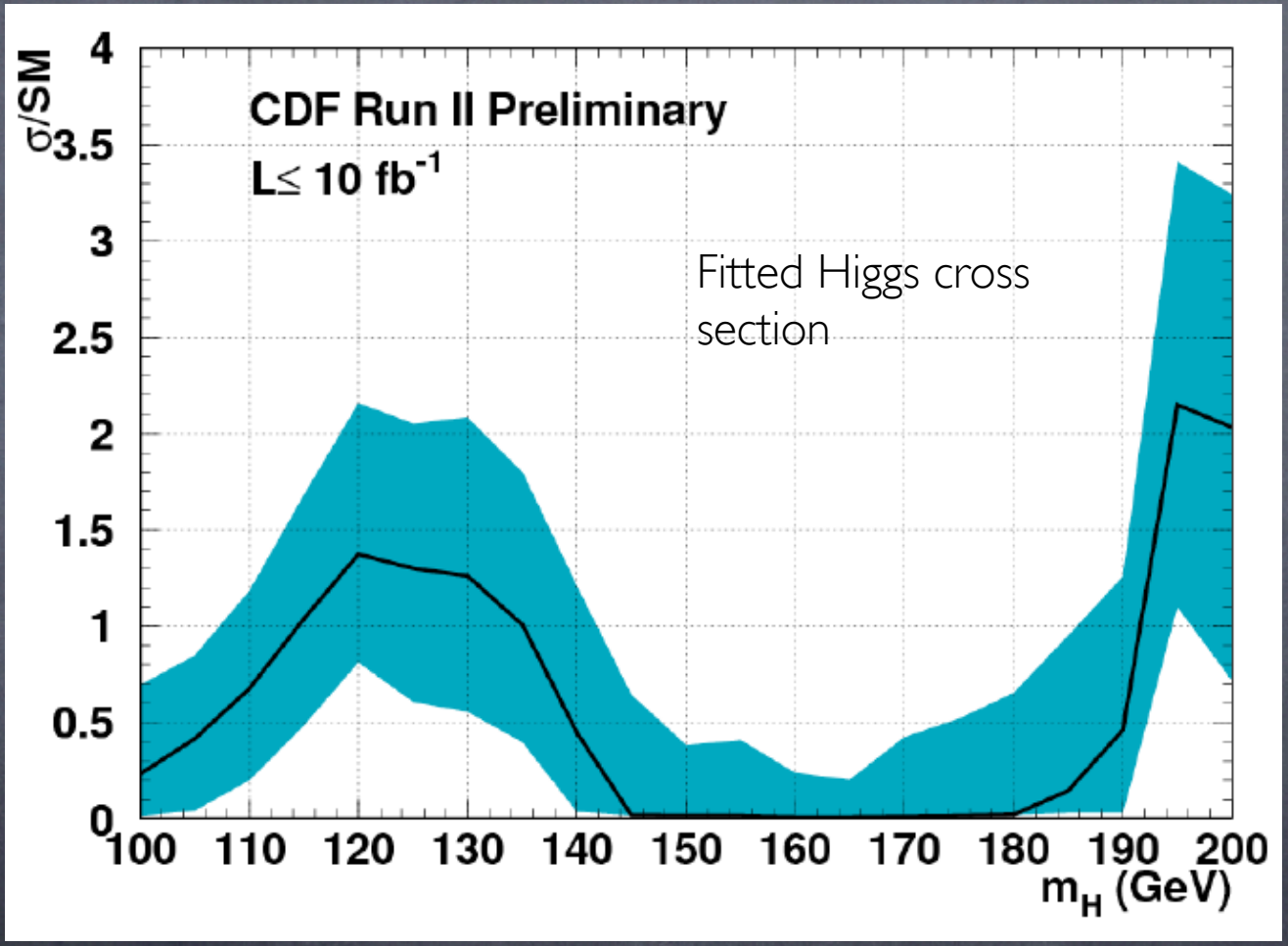
Global significance of excess

- Highest local p-value at m_H = 120 GeV/c^2
- mass resolution of searches, dominated by bb at low mass and WW at high mass, is broad
- Estimate LEE of 4 for our entire SM search range from 100 to 200 GeV/c^2



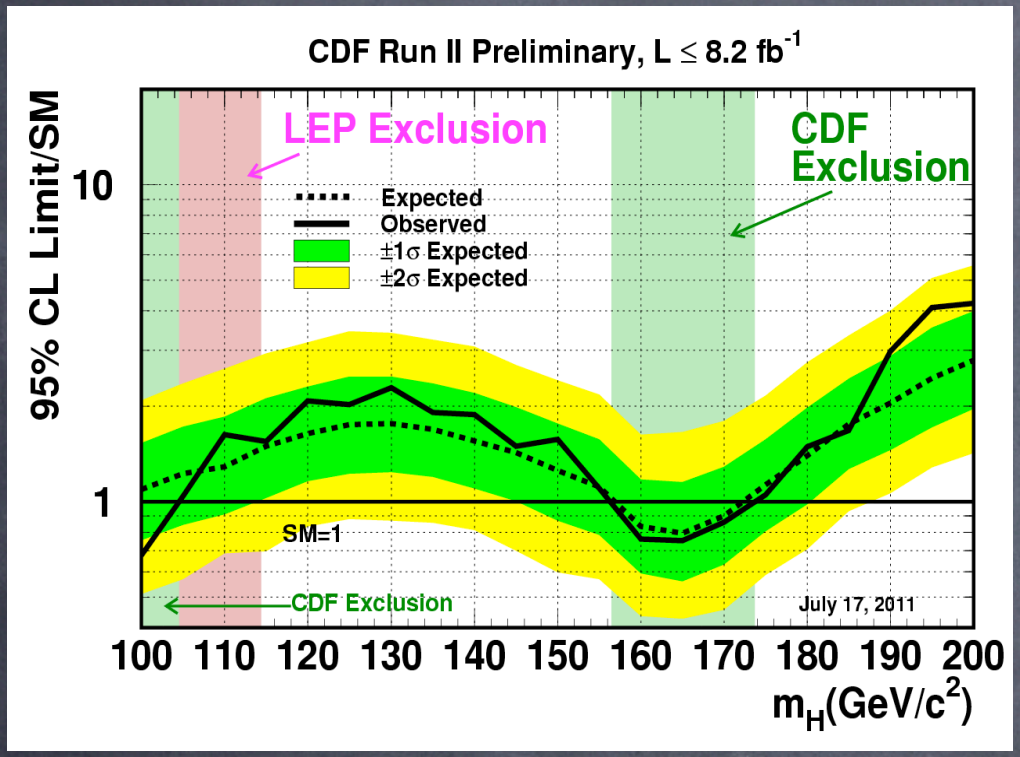
SM Higgs Searches		
Experiment	Local P-value	Global P-value
CDF	2.6σ	2.1σ

compatible with SM Higgs?

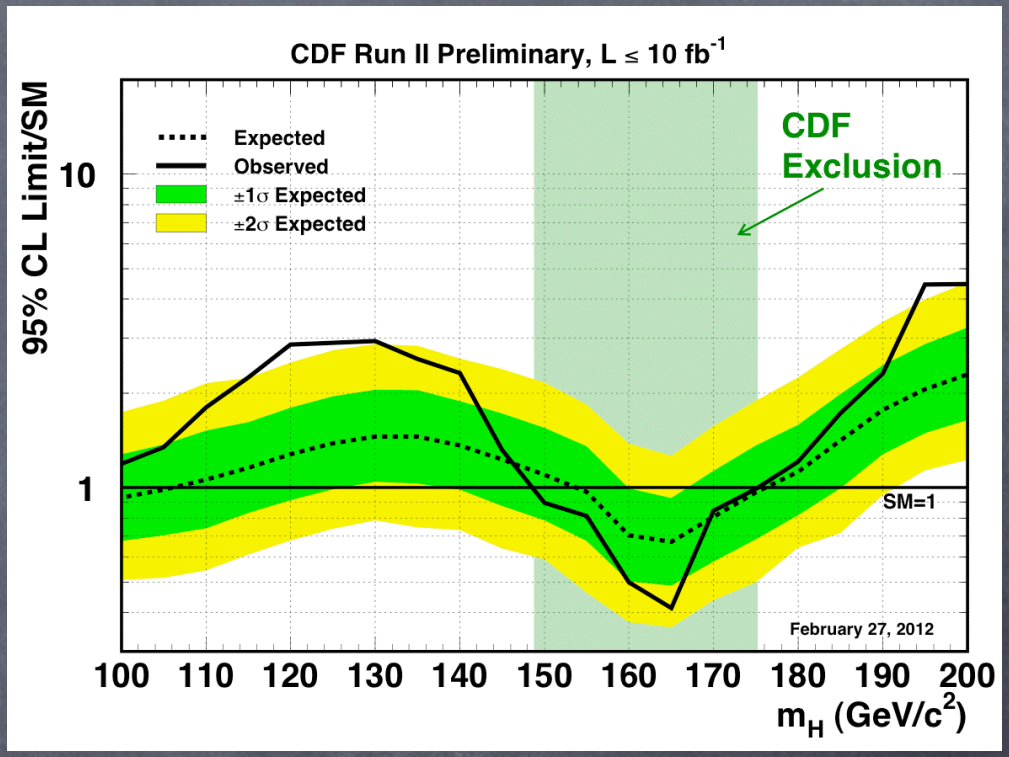


Consistent with SM Higgs at 1σ level for mass range between 107 and 142 GeV/c^2

how much did things change?



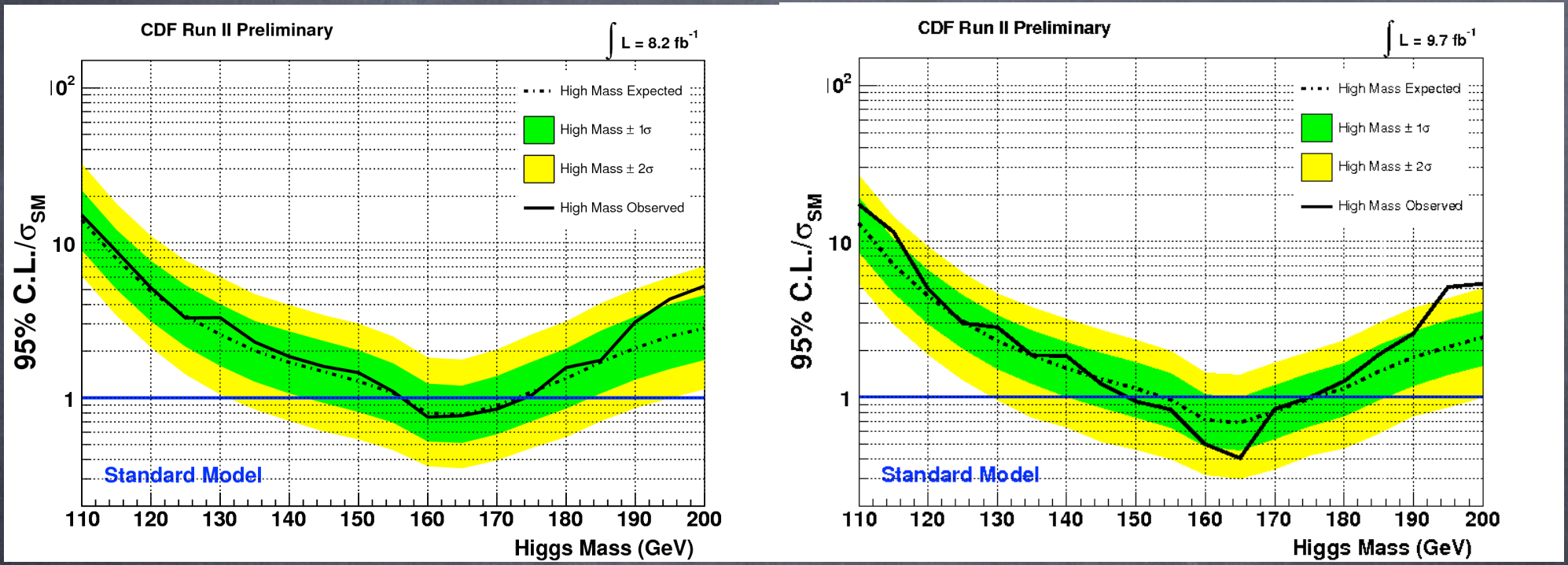
Summer 2011



Winter 2012

A ~0.5σ excess in mass range from 115 to 135 GeV/c^2 has become a ~2σ excess. How can this happen?

H→WW

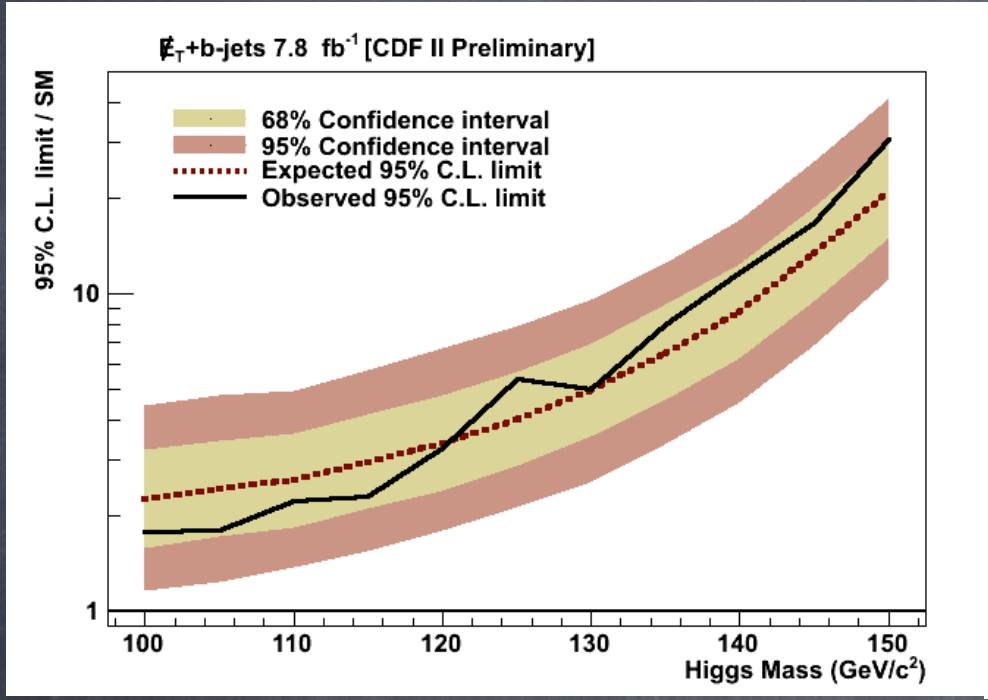


Summer 2011

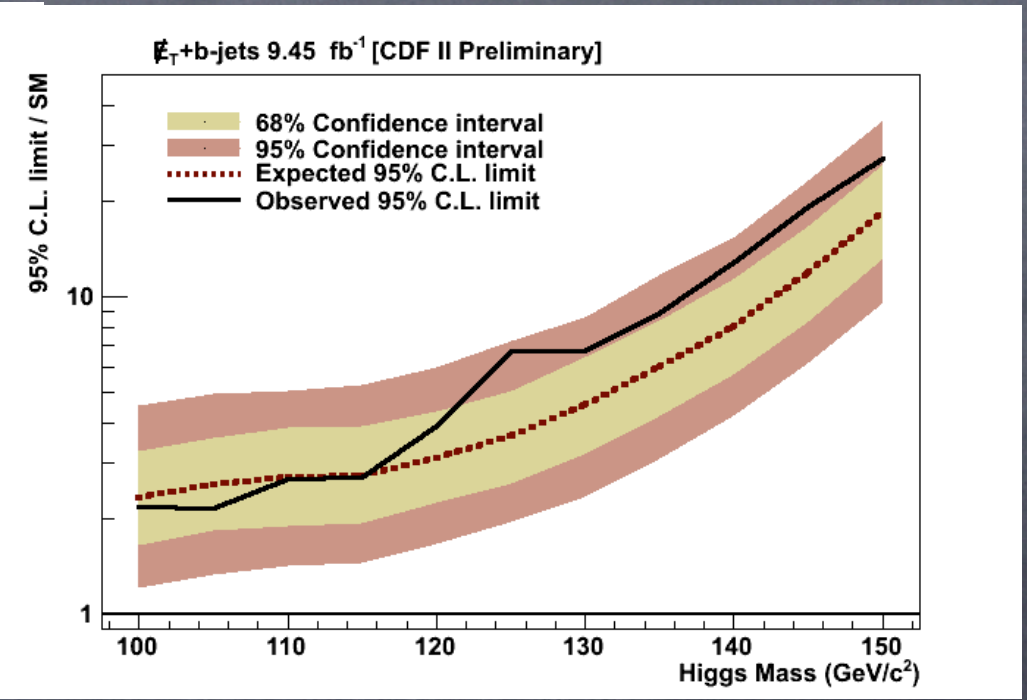
Winter 2012

- 18% additional data
- Small signal acceptance improvements ($0.1 < \Delta R_{ll} < 0.2$)
- No appreciable change in behavior of limits

ZH→ννbb



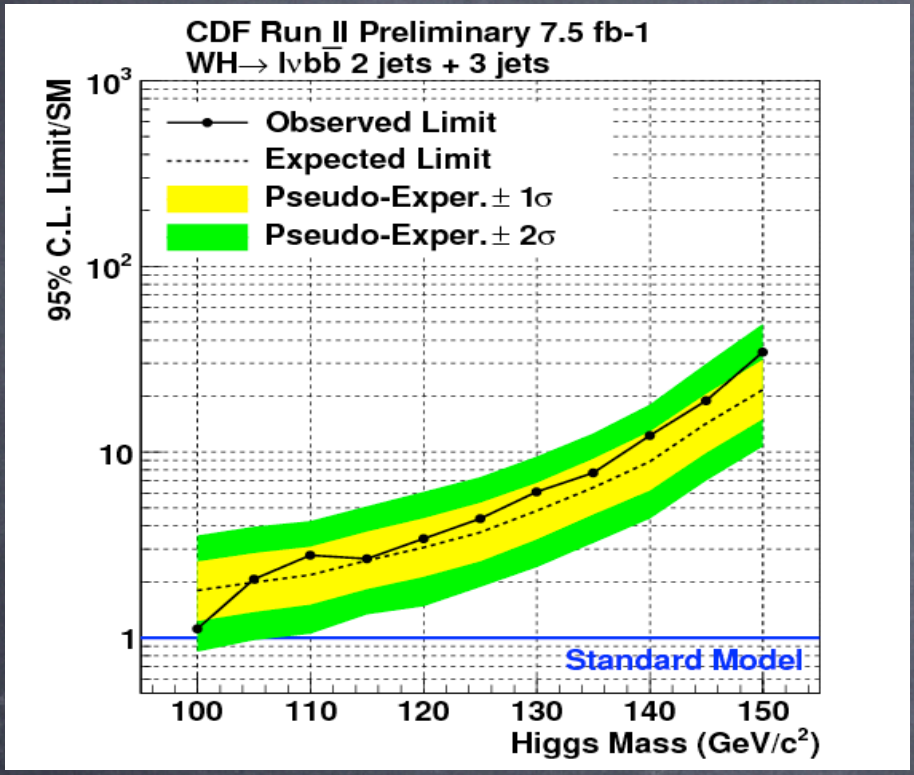
Summer 2011



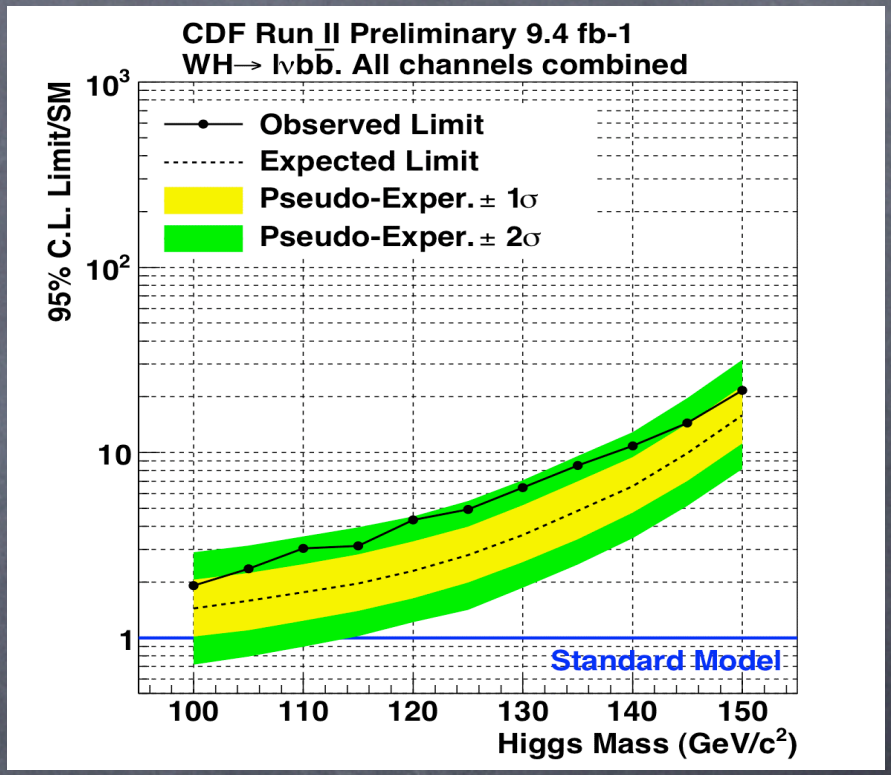
Winter 2012

- 21% additional luminosity
- Small improvements in background rejection
- same basic behavior w/ 0.5 to 1.0σ increases in significance of excess

WH→lνbb



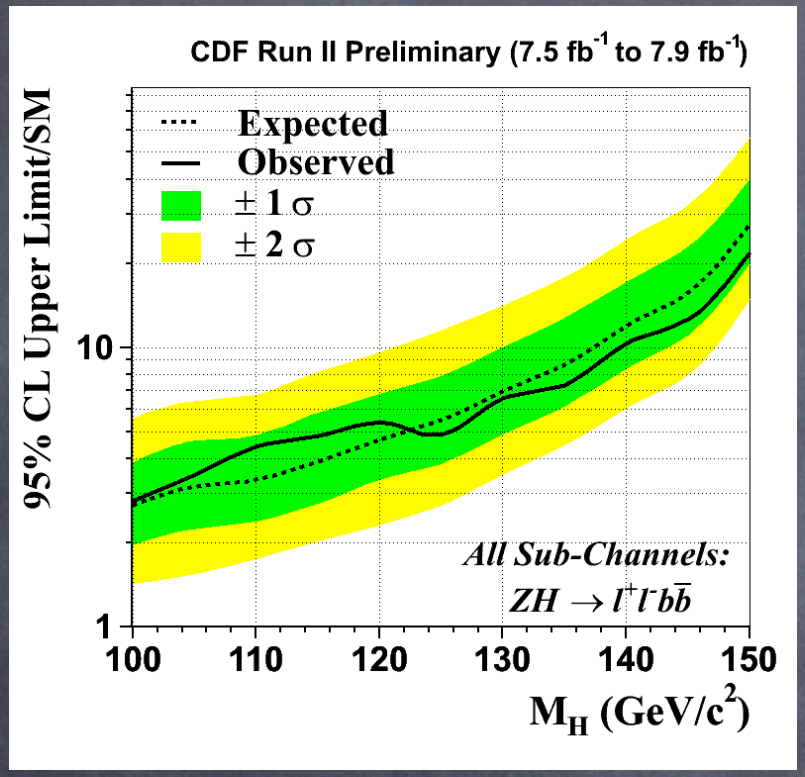
Summer 2011

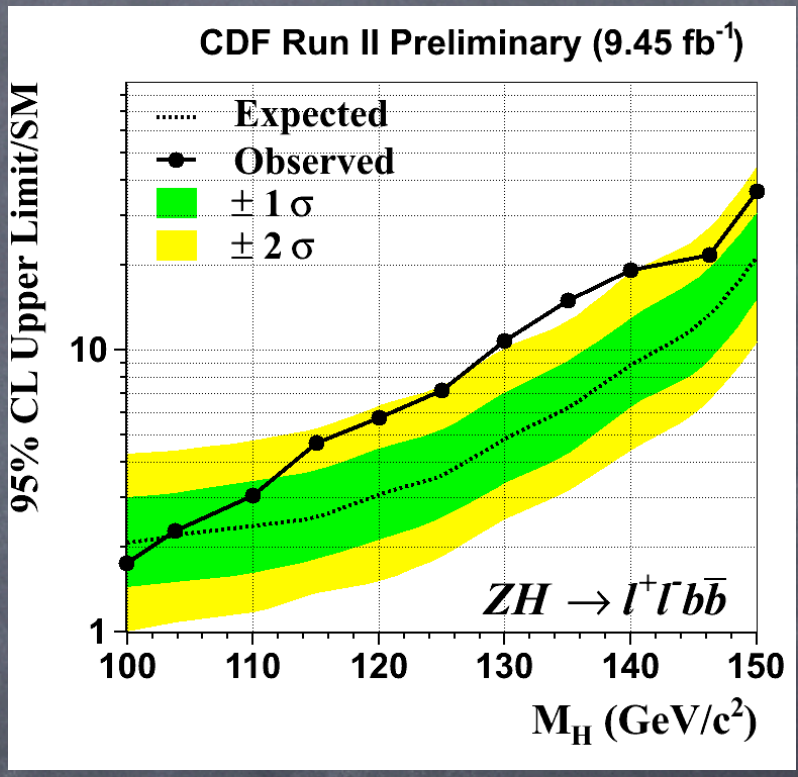


Winter 2012

- 26% (69%) additional luminosity for 2-jet (3-jet) channels
- 5-10% level lepton acceptance/trigger efficiency improvements
- New HOBIT b-tagger equivalent to adding another 20% in additional luminosity
- Limits show same basic behavior with 1.0 to 1.5σ increases in significance of excess

ZH→llbb





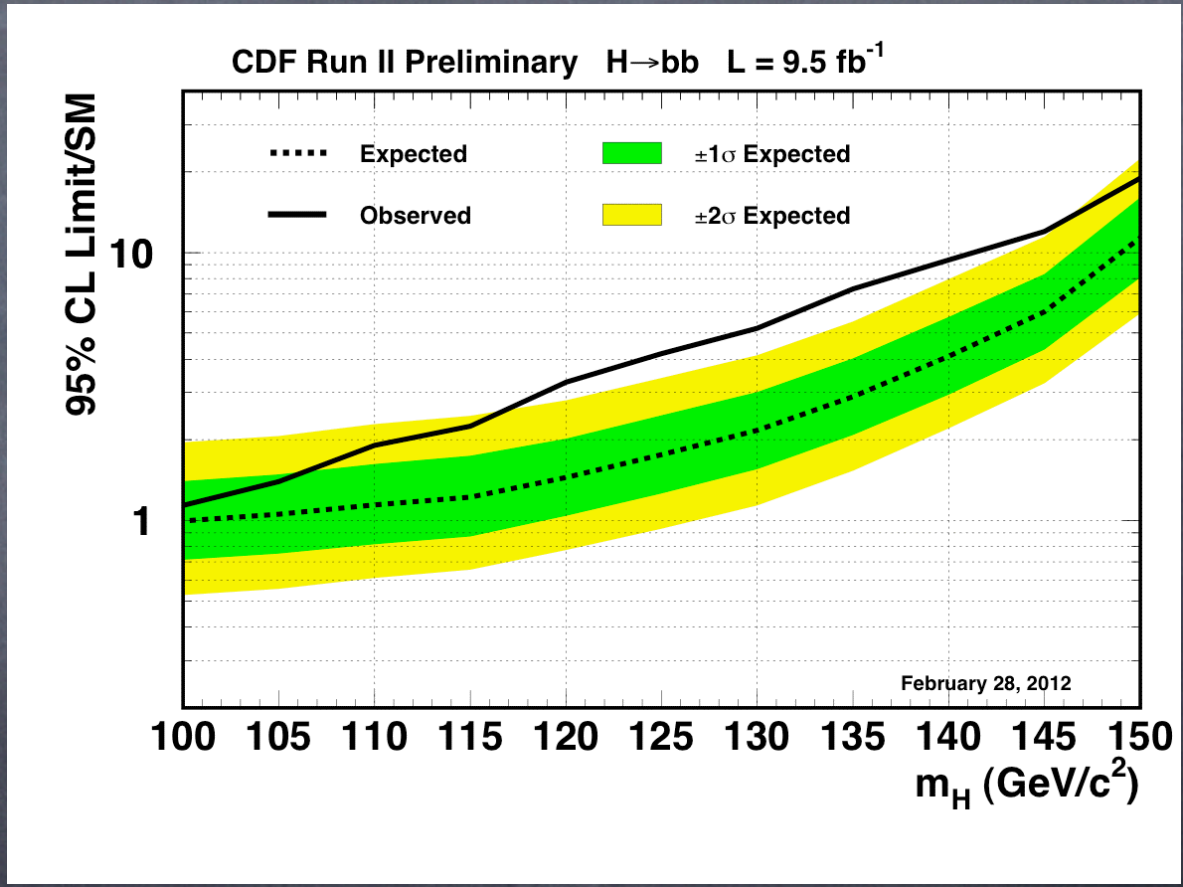
Summer 2011

Winter 2012

- 23% additional luminosity
- More gain from HOBIT in this analysis than WH (original tagging not as sophisticated)
- 56% of data events in current analysis were not included in previous analysis!
- 37% sensitivity improvement (4.67® 2.95 at m_H=120 GeV/c^2)

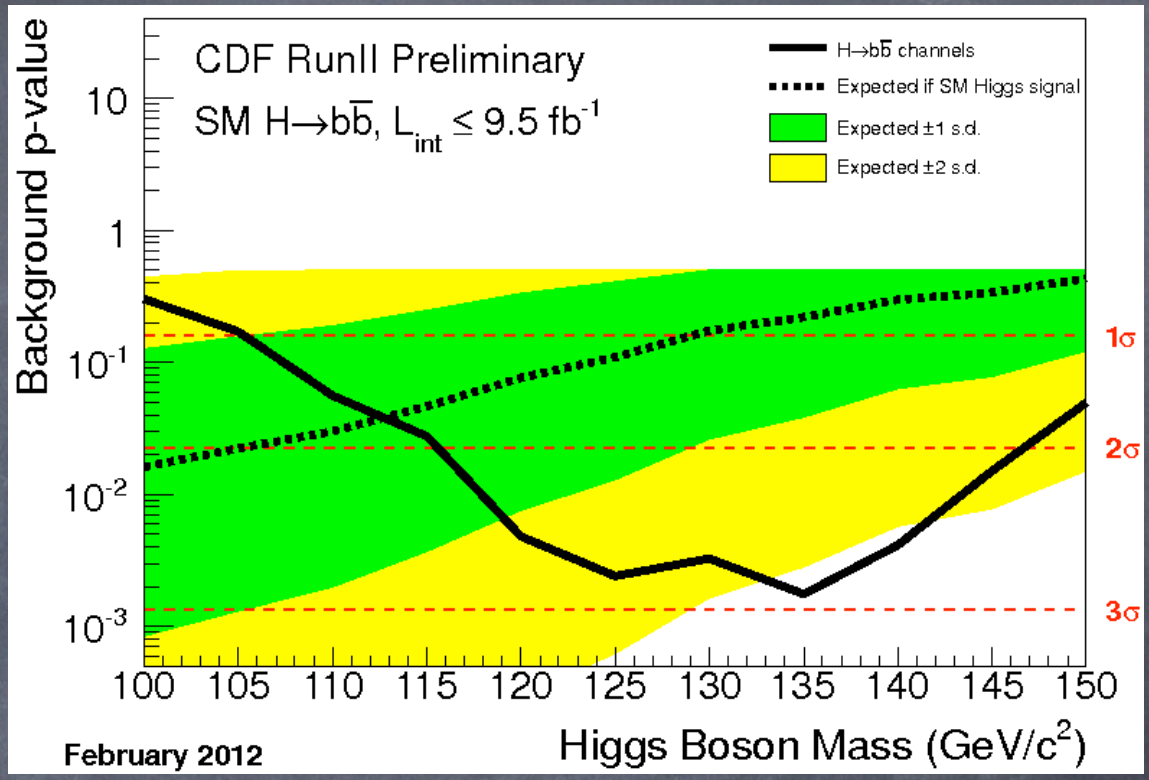
Tevatron strength: H→bb

- Combine our three primary low mass search channels
  - WH→lνbb
  - ZH→ννbb
  - ZH→llbb
- Allows for a quasi-model independent search for associated Higgs production with H→bb



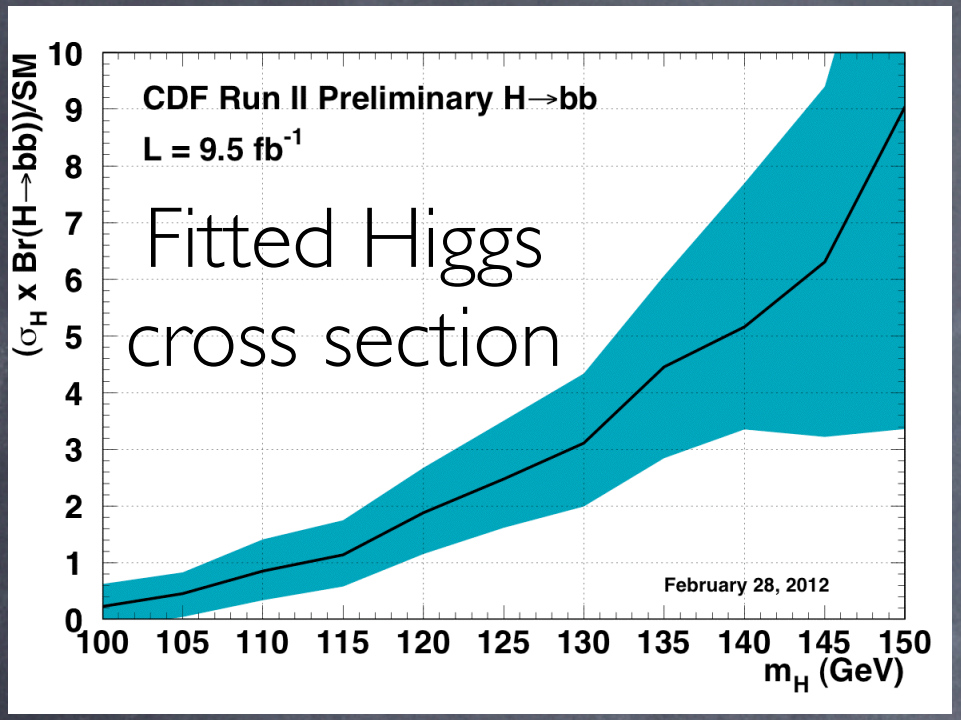
Global Significance of H→bb

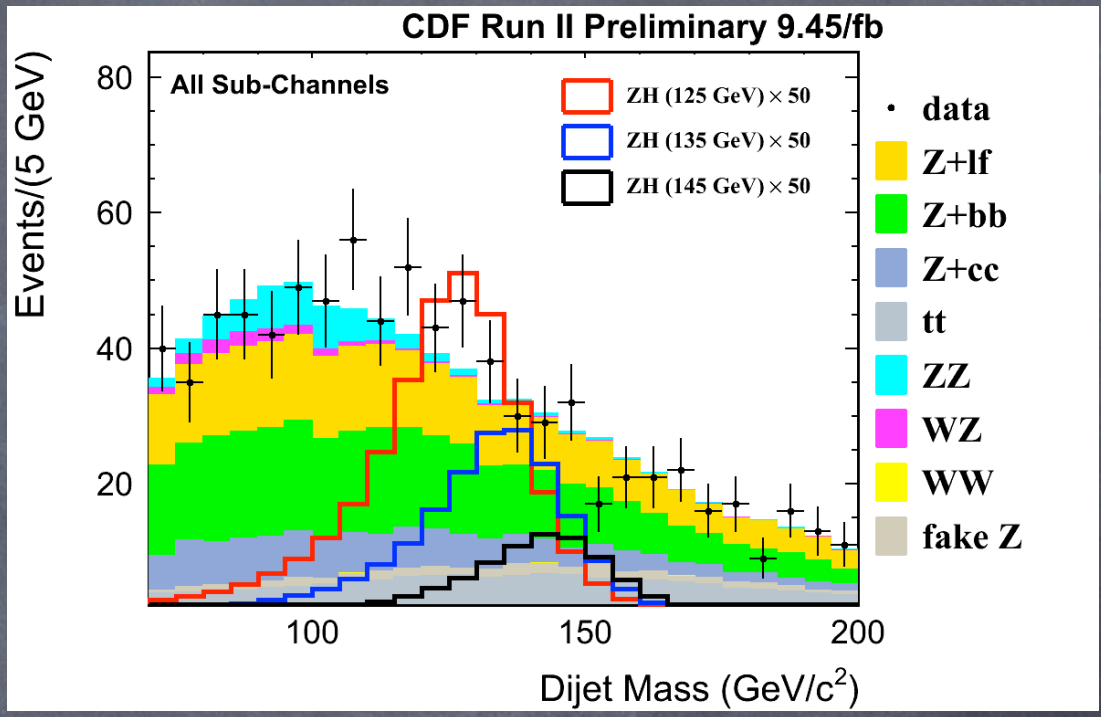
- Highest local p-value is found at m_H = 135 GeV/c^2
- These searches are performed in the mass range between 100 to 150 GeV/c^2
- Estimate LEE of 2



Single Channel Searches			
Experiment	Channel	Local P-value	Global P-value
CDF	H->bb	2.9σ	2.7σ

compatible with SM Higgs?

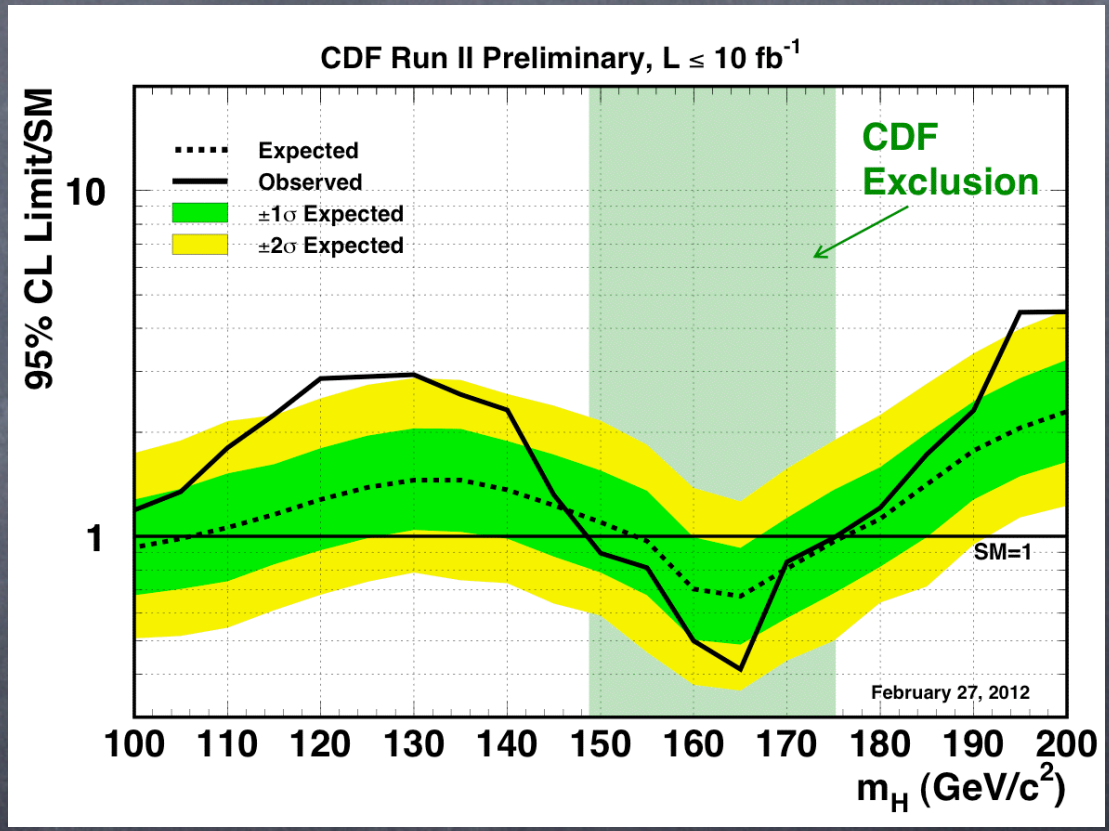




- Data are most consistent with SM in mass range from 105 < m_H < 120 GeV/c^2
- Behavior at higher m_H values is consistent with the expectation from a lower mass Higgs

CDF Conclusions

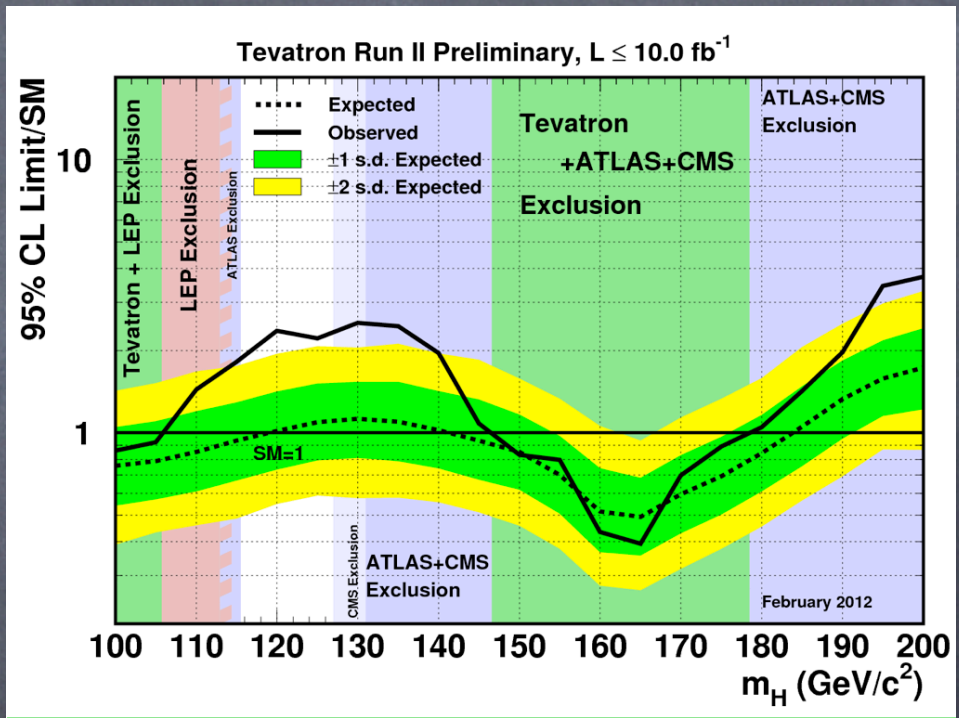
- CDF has significantly increased the sensitivity of its Higgs searches by incorporating the full 10 fb^{-1} dataset and a wide range of analysis improvements
- All SM searches combined
  - excess of Higgs-like events observed
  - consistent with SM Higgs production in the mass range from 107 to 142 GeV/c^2.
  - global significance of 2.1σ
- Associated Higgs production in the decay mode H→bb
  - excess of Higgs-like events observed, again consistent with SM Higgs production
  - global significance of 2.7σ



Backup

Tevatron Higgs Summary

- Tevatron delivered a spectacular dataset
- CDF and D0 incorporated full dataset into Higgs searches
- added considerable improvements to Higgs searches beyond luminosity
- measure VZ →X+bb at 4.6σ significance and consistent with SM
- Observe an excess of Higgs like event consistent with SM Higgs production
- global significance of excess is 2.2σ
- consistent with SM Higgs production



Tevatron Exclusion

$147 < m_H < 179$ GeV/c^2

optimal b-quark tagger for Higgs

- start with yields from previous taggers
- scale efficiencies and fake rates
- run pseudo experiments
- c-quark discrimination had minimal effect
- can afford an increase in fake rate

$WH \to \ell\nu bb$, 2jets CDF Run II Preliminary 7.5 fb^{-1}			
Total	ST+ST	ST+JP	ST+NN
Pretag Events	184050	184050	184050
$t\bar{t}$	142±22	114±12	62.8±6.4
Single top(s-ch)	45.0±6.7	35.1±3.4	18.9±1.8
Single top(t-ch)	13.9±2.4	13.3±2.0	8.7±1.2
WW	1.67±0.42	6.23±2.08	5.14±1.35
WZ	12.9±2.0	10.7±1.2	5.84±0.62
ZZ	0.62±0.09	0.49±0.06	0.29±0.03
$Z + jets$	9.64±1.40	11.9±1.7	8.75±1.30
$Wb\bar{b}$	257±104	228±91	125±50
$Wc\bar{c}/c$	31.0±12.6	98.3±40.5	63.8±26.0
Mistag	12.1±2.9	52.8±15.2	57.0±14.3
non-W QCD	57.9±23.6	85.3±34.1	74.9±29.9
Total background	584±169	656±194	432±126
Observed Events	519	568	402
WH and ZH signal (115 GeV)	7.28±0.98	5.34±0.39	2.80±0.19

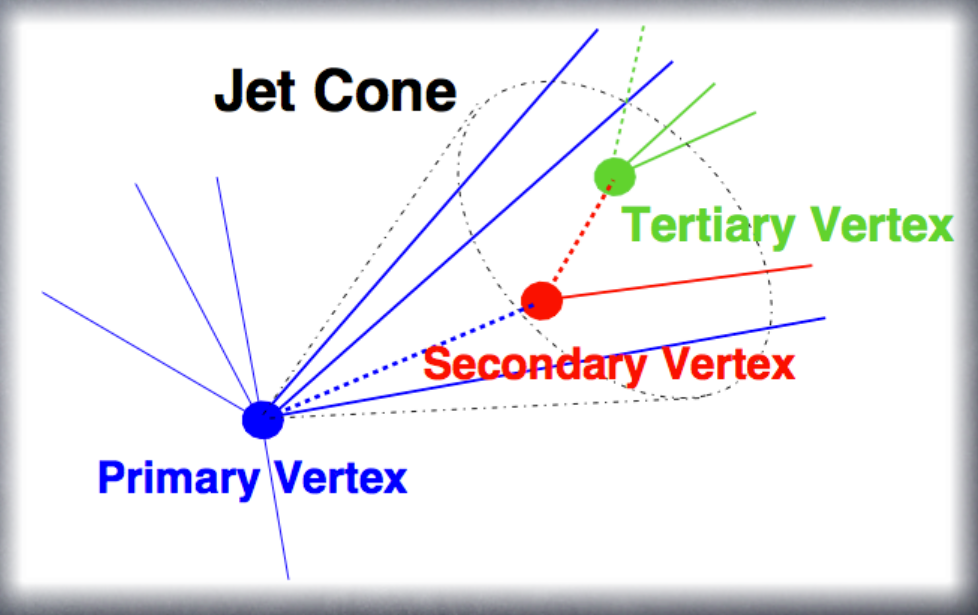
optimal b-quark tagger for Higgs

- start with yields from previous taggers
- scale efficiencies and fake rates
- run pseudo experiments
- c-quark discrimination had minimal effect
- can afford an increase in fake rate

- use select variables from older taggers
- combine into a single Higgs optimized Neural Network
- provide multiple operating points
- training with Higgs decay jets improves

HOBIT validation

- compare performance in simulation with data
- previous taggers utilized resolution effects to measure corrections
- no longer available in MVA tagger, but now how large orthogonal datasets
- measure correction scale factors using two newly developed techniques
- combine the two measurements to reduce the b-tag efficiency uncertainty



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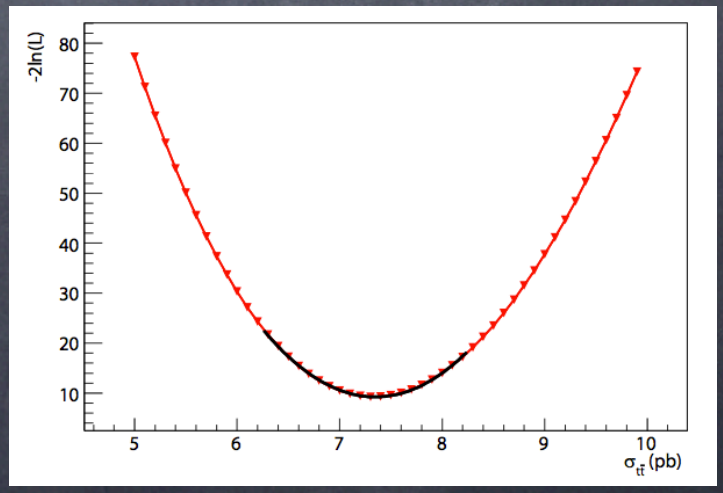
σ(tt) method

- previously measure σ(tt) and b-tag eff simultaneously
- select tt-bar enhanced data
  - W+3,4,5+ jet sample
  - W+1 jet sample
- fluctuate the b-tag eff and light-jet mistag efficiency
- perform 2D χ^2 minimization in b-eff SF and mistag SF



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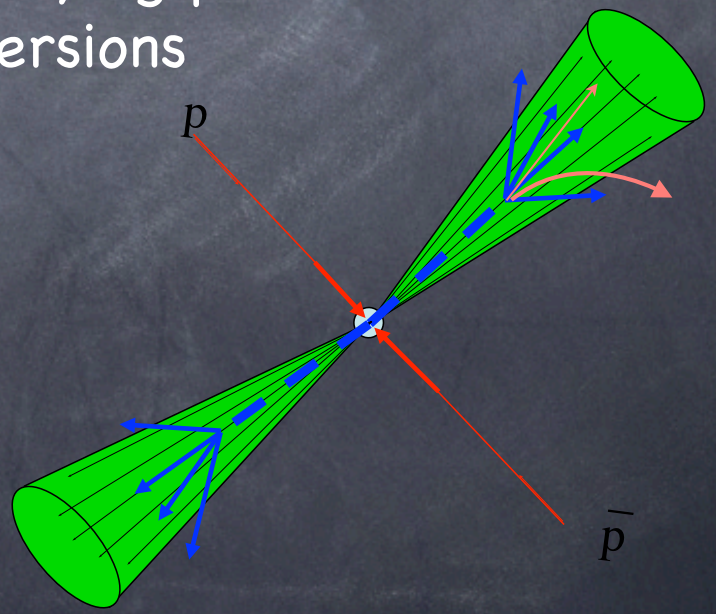
soft-electron method

- enhance b-content in a dijet sample with soft-electron tagging in away jet
- correct the heavy flavor content based upon identifying photon conversions



ZH→llbb

- Examine top 20 events in both channels based on S/B of the discriminant bin in which it's located
- The electron channel contains 12 new candidates within this high score region, while muon channel has 5